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Control of Root-knot Nematode in Greenhouses

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CONTROL OF ROOT-KNOT NEMATODE IN GREENHOUSES

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INTRODUCTION

Importance of the Greenhouse Vegetable Industry

The 14th Census gives some conception of the importance of the greenhouse vegetable industry. In 1919, 3,719 acres under glass in the United States were devoted to flowers and vegetables, worth $77,400,000. One-fifth of this amount represented receipts from sales of vegetables.

In Ohio flowers and vegetables worth more than $7,000,000 were grown on 445 acres under glass. The vegetable sales alone totaled $2,700,000. At that time, this acreage represented for Ohio an increase of about 250 acres since 1910.

Importance of Root-Knot Nematodes

GEOGRAPHIC RANGE AND LOSSES

Probably no pest attacking greenhouse vegetables has a wider range over the world than the root-knot nematode *Heterodera radicicola* (Greef) Müller, recently changed by Cobb to *Caconema radicicola* (Greef) Cobb. It stubbornly resists eradication and is devastating wherever conditions favor its development. It is known to occur in the oases of the Sahara, the Scandinavian Peninsula, England, Russia, India, and Australia. In the Western Hemisphere it is more or less abundant thruout the subtropical and temperate zones of both North and South America. The annual losses aggregate well into the hundreds of millions, and for the United States alone, several millions of dollars, Cobb (9).

In the United States, nematodes are more or less abundant on outdoor crops in the South Atlantic States, Gulf States, and in southern California. There is increasing evidence that *Heterodera radicicola* can live thru the winter as far north as the Great Lakes region. The authors have observed it on celery seedlings grown on muck in western New York. It is a serious pest in at least one celery muck district of central Ohio. It has been observed in abundance on peas and parsnips in northern Ohio, near Cleveland.

Bessey (3) states that it may be found on ginseng as far north as the Upper Peninsula of Michigan, where the soil usually freezes to a depth of more than three feet.

That nematodes are not a more serious handicap to the outdoor vegetable grower, in the northern states, is probably due not so much to their inability to endure the winters of the North as to their inability to multiply rapidly during the short summers. There is little doubt that the land in the immediate vicinity of nematode-infested greenhouses becomes contaminated by means of soil taken out with seedlings, tools, and on the feet of workmen. There are also cases on record near Cleveland, where greenhouses built over land previously intensively cropped to vegetables became badly infested the first season.

It is, however, in the vegetable greenhouse sections of Ohio and other northern states that the nematode problem exists in its most acute form. Fully 60 percent of the vegetable greenhouses in this state sustain heavy losses annually. In lettuce houses, where the average soil temperature is kept low (50° F.), nematodes do not become as severe as in houses where high-temperature crops, as tomatoes and cucumbers, are grown. On the conservative basis of $300 per acre as the average cost of steaming soil, it is probable that over $100,000 is now spent annually in Ohio in steaming greenhouse soil for nematodes. If steaming were not practiced, the losses would probably be more than five times this amount. In addition to this expenditure, according to our records, many thousands of dollars are thrown away by growers on quack nostrums for nematode control.

SUSCEPTIBLE, RESISTANT, AND IMMUNE PLANTS

As early as 1911 nearly 500 species of plants were known to be subject to attack by this nematode. The list of 483 given by Bessey (3) includes almost all of the more important families of flowering plants as well as one fern and one conifer. Monocotyledons and dicotyledons, herbs and woody plants, annuals and perennials, are all subject to attack. The following list of 37 crops (Table 1) taken from Supplements 26 to 30 of the U. S. Department of Agriculture, Bureau of Plant Industry, Plant Disease Survey Bulletin, 1923, indicates the wide variety of plants in the United States on which losses are annually sustained. These losses occur chiefly in the southern states bordering the Gulf, in the sugar beet states of California, Colorado, and Utah, and in the northern states east of the Mississippi River.

TABLE 1.—Economic Plants on Which Nematodes Were Reported in United States in 1923

Alfalfa	Cotton	Pepper
Almond	Cowpea	Potato
Apricot	Cucumber	Sugar cane
Bean	Dahlia	Sweet clover
Beet	Eggplant	Sweet potato
Begonia	Fig	Swiss chard
Cabbage	Golden seal	Tobacco
Cantaloupe	Lettuce	Tomato
Carnation	Okra	Turnip
Celery	Onion	Velvet bean
Chicory	Pea	Violet
Clematis	Peach	Watermelon
	Peony	

Immune crops are rare. In Table 2 is a selected list of plants reported as unaffected by nematodes when grown on infested land (3, 4, 12, 21).

TABLE 2.—Crops Immune or Highly Resistant to Root Knot

Grasses and cereals
Crab grass (**Syntherisma sanguinale** (L.) Dulac.)
Red Top (**Agrostis alba** L.)
Johnson grass (**Holcus halepensis** L.)
Oats (some varieties) (**Avena sativa** L.)
Ornamental grass (**Eustachys petraea** (Sw.) Desv.)
Barley (**Hordeum vulgare** L.)
Perennial Rye-grass (**Lolium perenne** L.)
Japanese barnyard millet (**Echinochloa frumentacea** Link)
Broom corn millet (**Panicum miliaceum** L.)
Pearl millet (**Pennisetum** sp.)
Timothy (**Phleum pratense** L.)
Rye (**Secale cereale** L.)
Wheat **Triticum aestivum** L.)
Sorghums, milos, Kafir corn, etc. (**Holcus sorghum** L.)
Corn (**Zea mays** L.)
Teosinte (**Euchlaena mexicana** Shrad)
Schrader's brome grass (**Bromus unioloides** (Willd.) H. B. K.)
Forage crops
Cowpea, Brabham, Iron, and Victor (**Vigna sinensis** (L.) Endl.)
Soybean, Laredo, Biloxi, and Orootan (**Soja max Piper**)
Peanut, bush and running type, (**Arachis hypogaea** L.)
Velvet bean, all climbing and bunch varieties, (**Stizolobium** sp.)
Composites
Bur marigold (**Bidens leucantha** and **B. bipinnata** L.)
Everlasting (**Gnaphalium purpureum** L.)
Sneezeweed (**Helenium tenuifolium** Nutt.)
Golden rod (**Solidago** sp.)
Zinnia (**Zinnia** sp.)

In the South control measures are based on a crop rotation in which the land is occupied successively by immune crops for a period of two to four years (12).

Life History of the Nematode, *Heterodera radicicola*

This parasite belongs to the true worms, differing from them by having no jaws nor body segments. Hatching from a colorless, transparent, oval-shaped egg about 1/250 of an inch long, the male and female worms find their way thru the soil to some young feeding root. At this stage the worms are so small that it would take about 32 of them end to end to span an inch. They bore their way into the cells of the root where they feed and grow. The irritation they set up causes the plant cells to enlarge. This hypertrophy is the only evidence of the presence of the nematode visible to the naked eye (Fig. 1). The irritating factor probably is chemical rather than mechanical and according to Steiner (30) seems to reside in the salivary glands of the young worm.

The young male worm (Fig. 2, A12) enlarges, sheds its skin and in three or four weeks is mature. It then seeks the female and effects fertilization. Thereafter the male soon dies; thus mature males are not easy to find. The female molts once, then matures, enlarges, becomes pear shaped and large enough to be seen with the naked eye (1/25 inch). She may lay 10 or 15 eggs each day until 300 to 500 are laid.[1] These egg masses are covered with a brownish the eggs may hatch in two to six days, or, if conditions of moisture and temperature are not suitable, the tough, elastic, chitinous shell, or membrane, of the eggs renders them capable of resting for long periods. In some cases the eggs probably hatch before ejection by the female. Once the female is deeply embedded in the tissues of the host the rest of its life may be spent within the plant. As many as 12 generations a year may develop in the south where temperatures are favorable the year round. But in the north there are probably not more than three or four generations out-of-doors. In greenhouses, in which winter cucumbers, tomatoes, or other susceptible high-temperature crops are grown, additional generations may appear. Bessey (3) states that the time required for the entire life cycle from egg to egg is probably not less than three weeks and it may be two months.

Environmental Factors in Relation to Nematode Activities

The root-knot nematode is highly sensitive to heat, drouth, freezing, and chemicals. McClintock (21) and Godfrey and Morita (15) have shown that the egg stage of *H. radicicola*, rather than the larval stage, is the most resistant to unfavorable environmental conditions. This finding suggests that the worm over-winters in the soil in the egg stage.

[1]Sandground (28), in South Africa, states that 60 is the more common number laid

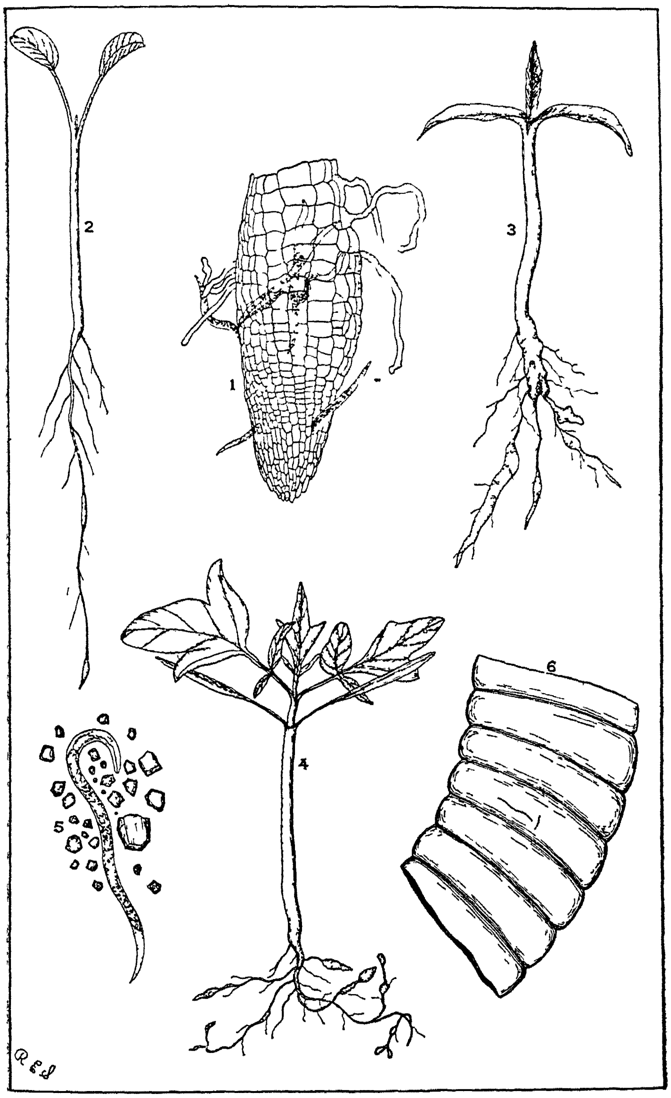

Fig. 1.—Size of the nematode, *Heterodera radicicola*, in relation to certain young seedlings and soil particles. 1, tip of cucumber root with young nematodes just entering, enlarged. 2, 3, and 4, seedlings of rape, cucumber, and tomato, from badly infested soil. 5, young Heterodera among the particles of a fine loam soil, x 175. 6, portion of an angle worm contrasted in size with Heterodera, represented by the two black lines near the center, the longer representing the length of the mature male, the shorter that of the young worm. After R. E. Smith, Mass. (Hatch) Agr. Exp. Sta. Bul. 55 : 1898.

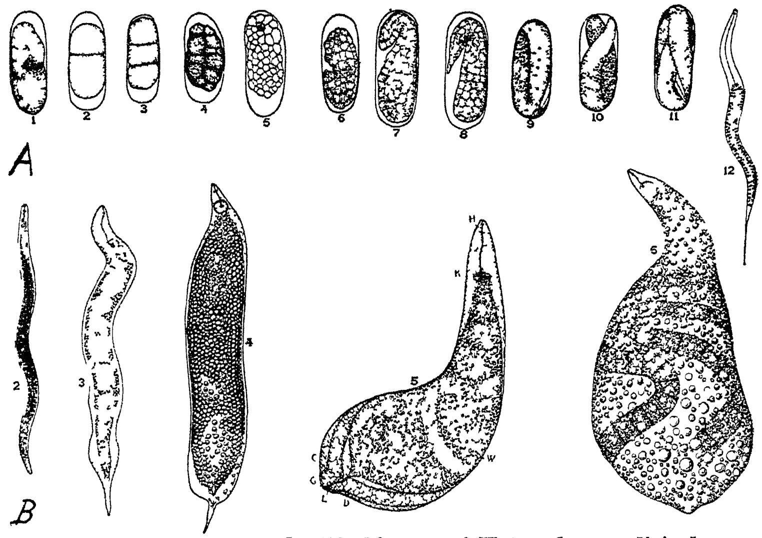

Fig. 2.—Stages in the life history of Heterodera radicicola

A. 1 to 11, (x 200) development of the worm within the egg; 12, (x 80) male worm. B. 2 to 6, (x 65) stages in the maturation of the female. Note immature eggs within the female in 6. After R. E. Smith, Mass. (Hatch) Agr. Exp. Sta. Bul. 55 : 1898.

TEMPERATURE

It is evident from observations and experiments that nematodes possess characteristic temperature limits. The type of crop, of soil, and size of galls seem to bear on this relationship.

The temperature at which the crop is normally grown is a factor in the occurrence of root knots. In greenhouses devoted to lettuce, which grows at temperatures from 45 to 60° F., nematodes are much less troublesome than in cucumber and tomato houses where temperatures of 70 to 75° prevail.

Godfrey (14) has shown that at a soil temperature of 59° F., injury from root knot is considerably less than at a temperature only 4 or 5° F., higher. At 50 to 54° infestations are rare on tomatoes. Infestations are known to be abundant in soil at 85°, and to occur to some extent at 102°.

The thermal death-point for Heterodera has been determined by Godfrey and Morita (15), who found that larvae are killed instantly at 128° F. and in 10 minutes at 110°. Egg masses are more resistant, being instantly killed at 137° and in 10 minutes at

119°. In our experiments the thermal death-point for all stages was between 116 and 120° in 10 minutes in ordinary loam soil (Fig. 3).

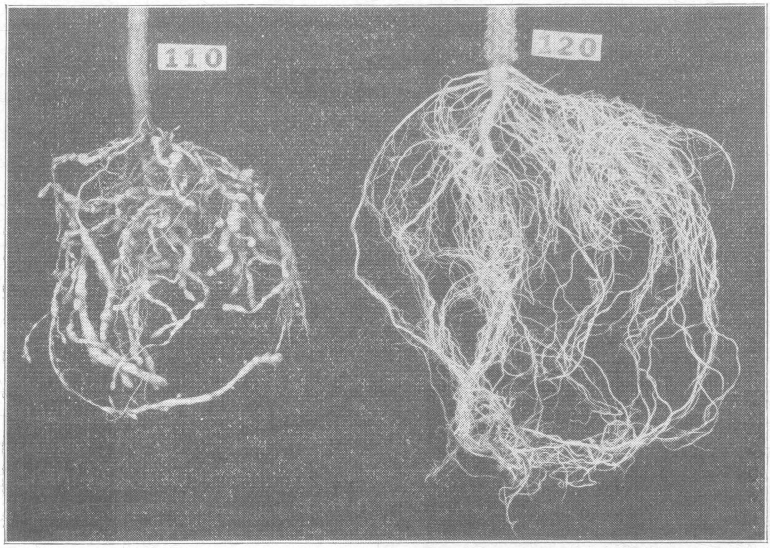

Fig. 3.—Tomatoes sowed in nema infested soil previously heated in a water bath for 20 minutes, showing that the thermal death-point of *Heterodera radicicola* lies between 110° and 120° F.

The lower temperature limits which this nematode can endure are not certainly known. Godfrey was unable to find that any stage, under laboratory conditions, could survive 2 hours exposure to temperatures of 0 to –4° F. Bessey (3) states that freezing is not fatal.

MOISTURE

Heavy infestation may occur over a wide range of soil-moisture content. Below 40 percent, which is too low for good growth of most crops, and above 80 percent, which is too wet, considerable root knot developed in Godfrey's experiments on such crops as tomato, celery, cucumber, lettuce, tobacco, and radish (13).

Extremes in soil moisture maintained over long periods will destroy the organism. Sandground (28) found that the larvae of one strain were destroyed in 3 days in water, while those of another strain died in 32 days. Truck growers in certain parts of Florida, whose farms are flooded for several weeks each year, claim for their soils freedom from root-knot troubles. In California flooding for a period of less than three or four weeks proved valueless in control, according to Bessey (3) and in Massachusetts flooding for a month failed to control, according to Jones (18). The normal position of the water table or the subsoil moisture condition may be the key to these opposite facts. Immature females or encysted eggs embedded in roots may thus be protected over long periods of flooding.

DESICCATION

Some species of nematodes will endure nine months desiccation, and according to one report *Tylenchus tritici* has been revived after 27 years in a dried condition (33). Fortunately, however, *Heterodera radicicola* is highly sensitive to drying. Godfrey and Morita (15) state that complete dryness kills larvae in three minutes and egg masses in two hours. Even in air at 70 percent relative humidity larvae die in 10 minutes and egg masses in four hours. Free eggs are more quickly killed than eggs in masses. Buried within roots egg masses can survive for 48 hours in a completely dry atmosphere. Protected in this manner they may survive for five days at 60 percent relative humidity, for seven days at 70 percent, and for an indefinite period at 90 to 95 percent. Godfrey and Morita also found in greenhouse tests that with soils 10 inches deep the organism was killed by four months of drying accompanied by occasional stirring. But, without stirring, the humidity in the soil interspaces at the lower levels was not sufficiently reduced to kill all the nematodes.

In our experiments on the effect of soil desiccation on nematode longevity, bench soil with heavily infested tomato roots was placed in eight shallow (1½ inch) flats. To determine the relative sensitivity of nemas embedded in roots and those free in the soil, the larger roots (⅜ inch) were screened out, cut into small pieces and placed in one of the halves of each flat. Thus, one half of each flat contained soil and only fine rootlets, and the other half contained soil with chopped galls of tomato roots. The flats, elevated one-half inch to permit air circulation, were placed on the concrete floor in front of a bank of radiators. The experiment was continued thruout April, May, and June. The soil temperature reached 80° F., or more nearly every day. Samples of soil were removed from the flats at daily intervals. Each sample was divided; a small portion was used for a moisture determination and the remainder placed in 4-inch sterilized pots and sown with tomato seed. After 28 days galls were observed in some of the pots, as shown in Table 3. After six weeks all the pots, 45 in number, were emptied and the roots washed and examined for galls. Nematodes had survived desiccation, at greenhouse temperatures which did not go over 85° F., until the eighth day by which time the soil moisture had been reduced to less than 3 percent (dry weight basis), or air-dryness. With one exception samples tested after the eighth day of drying showed no live nematodes (Fig. 4).

There is no doubt that soil can be freed from nematodes by complete drying. Deeper layers than those employed here (1½ inches) would require desiccation for a longer time, more stirring, or heat to hasten the drying process.

TABLE 3.—The Effect of Gradual Desiccation of Loam Soil on the Death of Nematodes as Indicated by the Development of Galls on Tomato Seedlings Grown Subsequently in Samples of the Soil

Number of days drying		0	2	5	6	7	8	9	10	13	19	180
Soil moisture (% dry wt.)	Series A (+ old roots)	....	.....	...	.....	3	2.6	1.5	5.9	1.8	2.1	. ...
	Series B (— old roots)	14.9	9.2	5.8	4.5	3	.6	1.4	2.1	1.4	2.1	2.93
Proportion of plants with galls after 6 weeks	Series A (+ old roots)	24*/24	24/24	34/35	33/36	26/27	0/26	0/26	1/15	0/28	0/25	.. ..
	Series B (— old roots)	25/25	24/24	34/35	30/36	13/29	0/20	0/30	0/14	0/30	0/26	0/21

*24/24 Numerator—number with galls on roots. Denominator—total number of plants examined.

This experiment and Godfrey's findings clearly suggest that pots and tools can readily be freed from active nematode contamination by placing them over a radiator or in the warm sunshine. It also suggests that old tools, walks, boards, dusty radiator pipes, and old shoes, if dried, will not be sources of recontamination of sterilized soil.

SOIL TEXTURE AND NEMATODE DISTRIBUTION

The root-knot nematode is much less injurious in a clay soil than in a sandy or muck soil. It is essentially a sandy or light soil organism. The soil pores may be too small in clay, the greater moisture content may inhibit the organism, or the temperature of clay soils may be too low for its development. Combinations of these factors may contribute to the relative freedom of heavy clay soils from serious nematode infestation. In northern greenhouses, wherever sandy soil grades into stiff clay, the root-knot nema has been found to be severe only in the sand. The sugar-beet nematode, on the other hand, will thrive in some of the heavier soils.

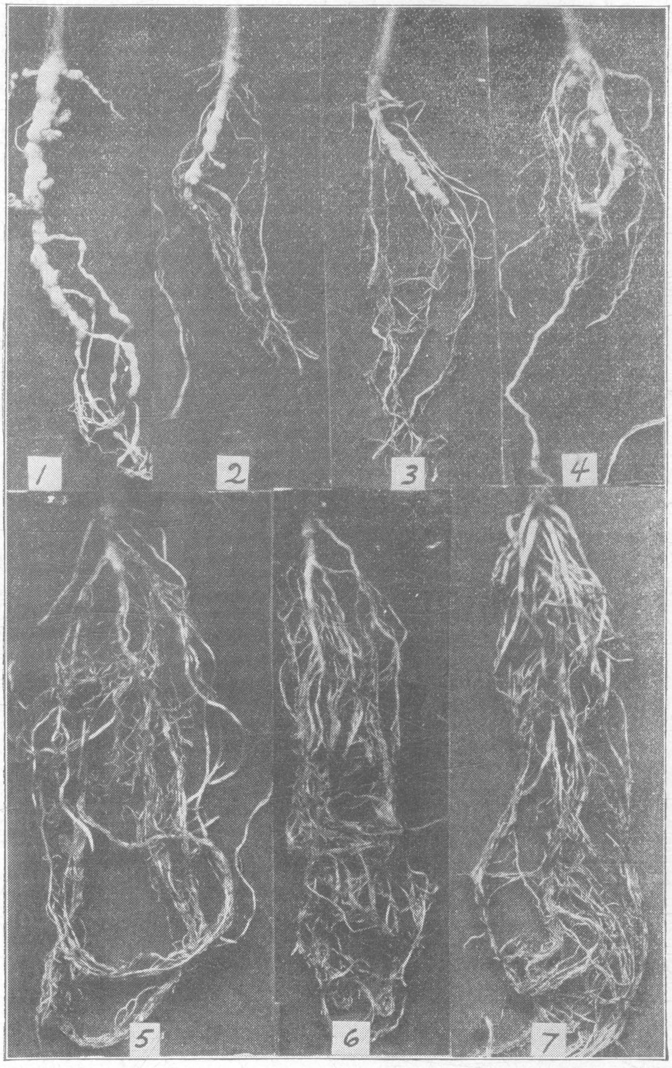

Fig. 4.—The effect of soil desiccation on its nematode population as determined by infection on tomato seedlings after 35 days' growth

1.	**Grown in original soil with**	**moisture content of**	**15%**
2.	**Soil previously dried 2 days,**	**moisture content of**	**9%**
3.	**Soil previously dried 5 days,**	**moisture content of**	**6%**
4.	**Soil previously dried 7 days,**	**moisture content of**	**3%**
5.	**Soil previously dried 8 days,**	**moisture content of**	**2.62%**
6.	**Soil previously dried 9 days,**	**moisture content of**	**1.71%**
7.	**Soil previously dried 180 days,**	**moisture content of**	**2.05%**

Note the freedom from galls on 5, 6, and 7. Similar freedom was noted in samples dried 10, 13, and 17 days.

DEPTH DISTRIBUTION OF NEMATODES IN SOILS

The depth at which nematodes are found varies with the texture of the soil, the water table, the kind of crops grown, the season of the year, and, perhaps, with the prevalence of the earthworm and of insect fauna. However, food, temperature, and soil texture probably are the chief factors that determine their depth distribution. Bessey (3) found them three feet below the surface of the soil. According to Godfrey (13) they were abundant in the sandy loam and hammock land of Florida as deep as he obtained samples (34 inches). On citrus roots in California and alfalfa in New South Wales, Cobb is said to have found certain kinds of nematodes 25 feet deep.

Probably in the greenhouses in the North they go fully as deep as out-of-doors in Florida. The author proved their presence in a sandy greenhouse soil as deep as 27 inches by growing tomato seedlings in samples of soil carefully removed from different depths. Furthermore, the roots of lettuce plants 11 weeks old have been observed to penetrate a sandy clay soil to a depth of more than 30 inches in a greenhouse near Cleveland. The roots followed the burrows of earthworms and so met with little resistance. It seems that these burrows, many of which were traced to a depth of more than 40 inches, very likely harbored nematode eggs and larvae.

CONTROL MEASURES

Immune Crops in the Rotation

Knowledge of crops that are not attacked by nematodes is of importance to the grower. In some types of farming rotation offers the most economical way of fighting nematodes. Crop rotations have been recommended for the south for many years. In these systems such immune crops as rye, corn, cowpeas, velvet beans, oats, or wheat occupy the land for a period of two to four years. Godfrey (12) recommends a rotation for the home garden of vegetables, followed in order by sweet corn, chicken pasture, and vegetables. This rotation would be quite applicable to a small area on which a greenhouse is to be built.

In the sugar-beet states of the West where the beet nematode, *Heterodera schactii*, is abundant it is the practice to rotate beets with such crops as alfalfa, peas, beans, sweet clover, or potatoes. For light infestations a 2-year rotation and for severe infestations a 5- or 6-year rotation have been found effective in reducing nematodes and greatly increasing yields, Thorne (34).

The northern vegetable grower who contemplates erecting greenhouses should consider the crop history of the land before building. If vegetables have been grown for a number of years, or if nematode infected nursery stock has occupied the land, he should postpone building and grow immune crops for at least two years.

Resistant Vegetables

Little progress has been made in the development of specifically immune or resistant vegetables.

Malloch (19) tested 67 varieties of cantaloupes and 98 varieties and 8 hybrids of tomatoes, finding them all susceptible to *Heterodera radicicola*. Apparently, little hope is offered by the results of this test. However, comparable work done with cowpeas indicates that the Iron and Brabham varieties are resistant in the South, Webber and Orton (36). On the other hand, Malloch (19) found these two varieties to be susceptible in California. These apparently conflicting observations may be explained by the existence of specialized races of the nematode. Further suggestion of such specialization is presented by Steiner (30). He points out that a given nematode population may become adapted to a given host to the extent that related plants are not congenial to it. When starved, however, this same population may attack a crop normally uncongenial. This adaptability offers real difficulty in planning a rotation to starve out the nematode.

While the work with vegetables would seem discouraging, yet encouragement is offered by tests made with sweet potatoes and fruits. Weimer and Harter (37) found among eight varieties of sweet potatoes three that were immune, three somewhat resistant, and two highly susceptible. McClintock (21, 22) reports a resistant factor in a certain peach to be transmitted to the first and second generations.

Doubtless a study of the fundamental nature of susceptibility and resistance should be made. Arzberger attributes resistance in certain cowpea varieties to the greater amount of protective tissue in the roots and to a reduced starch content in outer tissues of such roots according to Steiner (30).

In the light of the problems suggested, growers are advised to watch for resistant individuals of highly prized crop varieties. Should such resistant strains be found, their propagation might solve the problem.

Trap Crops

More than 40 years ago Kühn, in Germany, in fighting the sugar-beet nematode developed the use of trap crops. These consist of thick plantings of certain very susceptible, cheap crops like wild mustard on which the nematodes will become established. Then, before they have had time to lay their eggs and produce another generation the crops are pulled and burned. If this process is repeated two or three times, many nematodes are removed from the soil. But, practically, it has not met with great success in America. It is out of the question as a practice for greenhouses, according to the authors' observations. In each of three trials, one trap crop of lettuce was removed 28 days from sowing and a second lettuce crop set in its place. The roots of the second crop showed practically the same infestation in soil where a trap crop had and had not been grown.

Predaceous Nematodes

The soil at times may be inhabited by millions of carnivorous worms. The possibility of their use in the control of nematodes has been suggested by Cobb (9). The observations of Steiner and Heinley (31) strongly suggest that one predaceous species *(Mononchus papellatus)* can destroy great numbers of *Heterodera radicicola.* The actual importance of these carnivores in greenhouse soil is unknown. However, that they may be a factor in reducing nematodes is suggested by the observation that root knot sometimes disappears rather mysteriously.

Chemicals as Nemacides

HISTORICAL

In Germany, Kühn and Hollrung, who made more extensive chemical tests than any other European investigators, employed a large number of substances in experiments carried over a long period of years in an attempt to control the sugar-beet nematode. Their success was indifferent to such an extent that they turned their attention to the catch-crop method of fighting the pest. In France, some success was claimed from the use of ammoniacal liquor from gas works.

In the United States, Neal (23) had some success with kainit mixed with tobacco dust; and from among the several chemicals used in Florida tests, alkaline solutions were the most promising.

In Massachusetts, Stone and Smith (32) used a number of chemicals both in the greenhouse and outside. Pure ammonia killed free adult worms, but none of the substances tested on the soil gave positive results. More recently, Watson (35) discovered the nemacidal properties of calcium cyanamide. When used at the rate of one to three tons per acre, this material not only reduced the nematode population but acted as a nitrogenous fertilizer. Since extermination was not complete and scorching of plants followed its use, calcium cyanamide has not been generally adopted by growers. In field experiments hydrocyanic-acid gas liberated in loam soils from sodium cyanide and commercial ammonium sulfate was found ineffective in destroying nematodes, Byars (7). The work of McClintock (20) throws some light on the difficulty of obtaining complete killing with chemicals. He found the egg stage very resistant, even to a 30-minute immersion in formaldehyde, 1-10; sulfuric acid, 1-50; lime-sulfur, 32° Baumé; or copper sulfate, 20 percent.

During the last 75 years many substances have been employed either as direct nemacides or indirectly as fertilizers. While a discussion of each is not warranted, it is, nevertheless, of interest to note the extended list of materials used elsewhere than in Ohio, none of which has proved very satisfactory in controlling nematodes:

> Acetic acid, superphosphate, ammonia vapor, ammoniacal liquor of gas works, ammonium silicofluoride, ammonium sulfide, ammonium sulfate, ammonium sulfate plus lime, black-leaf 40, benzol vapor, dry and liquid calcium carbide, calcium sulfate, carbolic acid, carbon disulfide, carnallit, copper sulfate 20 percent, cresol, cresylic acid, cyanamide, Cyanogas, formaldehyde, gasoline, hydronaphthol, kerosene emulsion, kainit, lead arsenate (acid), lime (quick, slaked, and as lime water), lime-sulfur, lye, magnesium sulfate, manganous sulfate, naphthalene, paradichlorobenzene, phenol (Lettles solution), potassium chloride, potassium cyanide, potassium hydroxide, potassium permanganate, potassium sulfate, potassium sulfide, potassium sulfocarbonate, potassium xanthogenate, sodium chloride, sodium nitrate, sodium sulfate, sodium sulfide, sodium sulfo-carbonate, sodium xanthogenate, sulfuric acid, sulfur (ground and inoculated), tobacco dust, tobacco dust plus kainit, tobacco decoction, unleached ashes, and zinc sulfate.

EXPERIMENTS WITH CHEMICALS, 1925

In spite of the negative results obtained by previous workers the author determined to try control methods with chemicals. The task was made hopeful by several facts. deOng (25) pointed out the advantages of hydrocyanic-acid gas as a soil fumigant against a variety of insects. Cyanide in powder form is now easy to obtain, and some growers in other states have claimed success with it as a nemacide. Gardner (10) claims to have freed plants from nematodes by the use of paradichlorobenzene, which is also easily obtained on the market. Furthermore, recent work on the control of oat smut has shown that sometimes when single chemicals fail to control, combinations of two or more may give excellent results. This fact opens up much of the older work for re-investigation. And, lastly, large quantities of commercial preparations, such as "Fertaps" and Zotokos", were being widely sold in Ohio as nemacides, the use of which has resulted in many controversies.

FIRST GREENHOUSE EXPERIMENTS WITH LETTUCE

Thru the generous cooperation of M. L. Ruetenik of Cleveland, space in a greenhouse was obtained in the fall of 1924. The soil, a sandy loam, was thoroly infested with nematodes. Mr. Reutenik at that time practiced annual steam sterilization on the entire four-acre plant by means of the inverted pan. An area 110 by 15 feet was left unsterilized in the fall. This area permitted two series of 14 plots, each plot 7 feet square.

On December 26 and 27, barriers of heavy building paper were placed to a depth of 15 inches around each plot. The several chemicals were applied and thoroly forked in to a depth of 6 or 8 inches, after which a light application of water was made. Eleven days later a crop of lettuce was set, care being taken to avoid contaminating any plot with soil from another. Rubber boots were worn, and these were dipped in a strong formaldehyde solution before passing from one plot to the next. Arrangement of the plots permitted cultivation of the plants from the side without stepping on the soil. The purpose in growing this and the following lettuce crops was to determine the degree of injury occasioned by the various treatments. Also the lettuce served as a filler until time for setting the tomato crop. The tomatoes occupied the soil for several months and thus tested the efficiency of the various treatments in destroying nematodes.

Since the temperature for the lettuce was kept at 45 to 55° F., there were no nematode galls on any of the roots. It was apparent that many of the chemicals had a depressing effect on the yield of lettuce. Sodium cyanide, paracide plus carbon tetrachloride, the maximum dosage of cyanamide plus superphosphate, thymol, and naphthalene flakes plus carbon tetrachloride caused considerably more injury than the other chemicals. None of the treated plots yielded as much as the highest yielding check plot.

SECOND LETTUCE CROP

The second crop of lettuce was set March 17, 1925. Precautions were taken as before to avoid all possible contamination. The plants prior to setting were grown on steam sterilized soil. At this time Plot 6 was treated with calcium cyanide at the rate of 650 pounds per acre. Plot 23 was given twice that amount, the material being forked in thoroly. The lettuce on these two plots was not set until March 27. At that time the tomato plants were also set on all the plots, 16 to the plot, 13,900 per acre. On that date also, "Fertaps" and "Zotokos" were added to Plots 2 and 27 by their manufacturer and vendor. A rough analysis indicated these materials to be by-products of the steel mills and that they contained iron oxid.

The temperature for these lettuce and tomato crops was held between 55 and 65° F., until May 15, a compromise between the optimum for lettuce and that for tomatoes. On May 7 and 15 the lettuce was harvested and the roots of 10 to 15 plants from each plot were examined. Nematodes were found in all of the plots regardless of treatment. The variation among the check plots was as much as that among the differently treated plots; therefore, little of importance can be attached to the observed differences. The yields are given in Table 4.

FIRST TOMATO CROP

It was thought that the tomato crop would prove to be a more sensitive indicator of the worth of the treatments, therefore, a heavy mulch of manure was laid down between the rows and careful yield records kept. At the end of the season the roots were examined for evidence of nematodes. By the end of August there were nematode galls in abundance on the tomato roots on all plots. The greatest amount of stunting due to the chemicals in the soil was noted on Plots 3, 4, and 26, (cyanamide) and 5, 11, and 13 (cyanide and ammonium sulfate, thymol, and calcium cyanide, respectively). Since the plants on the cyanamide plots were very green at the close of the experiment and still bearing fruit, the yield undoubtedly would have been increased if the tomatoes had been allowed to ripen. The irregular yields and size of plants on the check plots diminish the significance of these yield data. Table 4 gives the 19 different treatments and the yields of the first and second crops of lettuce and 19 pickings of tomatoes.

EXPERIMENTS WITH CHEMICALS, 1926

LETTUCE AND TOMATOES

Since the experiments in 1925 were not conclusive and it seemed desirable to test several other chemical combinations, experiments on a larger series of plots were made during the winter of 1925-26. A house in which nematode infestation was severe and uniform and from which wilt and root rot were apparently absent was chosen for the experiment. The house, which is 110 by 30 feet, was divided into four series of 14 plots each. The series were lettered A, B, C, and D across the house and the plots in each were numbered 1 to 14. Each plot contained 50 square feet. Of the entire 56 plots 18 were left as checks.

TABLE 4.—Yields of First and Second Crops of Lettuce, and of Tomatoes on Chemically Treated Plots, March 16 and May 7, 1925. Treatments Were Made December 27, 1924

Plot	Treatment	Rate per acre	Lettuce Green weight		Tomatoes total wt. of fruit
			First crop	Second crop	
			Oz.	*Oz.*	*Lb.*
1	Check, none	....	No record	230	24.7
2	Check	....	66	140	29.3
3	Cyanamide	2,600 lb.	91	121	12.6
4	Cyanamide	1,300 lb.	106	64	19.8
5	Sodium cyanide Ammonium sulfate Calcium cyanide	1,080 lb. 1,080 lb. 650 lb.	none	112	28.7
6	Calcium cyanide	650 lb.	145	140	38.0
7	Carbon disulfide	135 gal.	101	176	50.0
8	Check, none	....	112	233	40.5
9	Paradichlorobenzene Carbon tetrachloride	216 lb. 135 gal.	41	221	46.5
10	Inoculated sulfur	1,500 lb.	94	214	45.1
11	Thymol	†	46	179	17.3
12	Iron sulfate Arsenic trioxide	†	105	210	13.2
13	Calcium cyanide	650 lb.	113	176	23.0
14	Check, none	....	....	222	37.1
15	Check, none	....	....	268	32.1
16	Calcium cyanide	1,300 lb.	116	227	28.7
17	Iron sulfate dust	†	96	164	19.6
18	Check, none	....	111	189	14.4
19	Tobacco dust	435 lb.	104	159	53.7
20	Naphthalene flakes Carbon tetrachloride	435 lb. 270 gal.	77	171	62.6
21	Check, none	....	65	226	52.3
22	Carbon disulfide	270 gal.	102	225	52.0
23	Calcium cyanide*	1,300 lb.	122	119	32.2
24	Cresylic acid*	1,300 lb.	93	232	28.8
25	Cyanamide Acid phosphate*	1,700 lb. 870 lb.	66	97	16.8
26	Cyanamide* Acid phosphate, 16%	2,600 lb. 1,300 lb.	43	59	9.68
27	Check*, none	....	65	193	28.4
28	Check, none	....	....	196	22.0

*Plants not large enough to harvest on May 7; were harvested on May 14. Their yields are therefore only comparable to each other.

†Material arrived too late for application.

On March 10 to 12, 15-inch trenches were dug and barriers of heavy creosote-impregnated, slate-covered felt roofing were buried vertically around each plot. A 3-inch projection above ground was left to prevent washing of top soil from plot to plot. The chemicals were applied and forked under March 12, and the lettuce was set March 13.

On March 19 it was necessary to replace the lettuce on the naphthalene + Cyanogas plots, cresol plot (C 8), and Cyanogas plots (Table 5). Some of the lettuce plants were so injured by Paracide, naphthalene, and cresol that resetting was necessary. In fact, the lettuce was twice reset but developed poorly on the nicotine + sulfur + Paracide plots, cresol plot, and picric acid + bleaching powder plot. Tomatoes likewise were stunted more or less by the bleaching powder + picric acid and by the Paracide.

Symptoms which the tomatoes developed on the plot treated with picric acid + chlorinated lime, were particularly interesting on account of their close resemblance to those of tomato mosaic. The new leaves showed many puffed areas and were distinctly mottled. In addition to the mosaic-like symptoms, the lower leaves took on a light bronze cast and the veins turned a purplish color. The plants were markedly stunted thruout the season but, after about 6 weeks, outgrew the mosaic symptoms of mottling and puffy leaves.

The irregular amount of infestation made it again impossible to draw reliable conclusions when the lettuce was harvested, April 13. It was hoped, however, that the tomato crop would give more definite results.

After harvesting the lettuce the customary mulch of well rotted manure was spread between the tomato rows. On top of this mulch a narrow board walk was laid so that the feet of workmen did not come in contact with the soil. Table 5 gives the yield from 24 pickings of tomatoes obtained over a 7-week period, June 16 to August 6, 1926. The relative nematode infestation was estimated by examining 8 to 16 vines from each plot.

When the soil was turned on Plot A5, five months after making the application, the odor of Paracide was still present. The roots of the tomatoes were abnormally crowded into the first two or three inches of soil. The nematode infestation on B11 and B12 was somewhat irregular, suggesting that the fluorides may have had a slight nemacidal effect. The effect was even more pronounced on Plots C7, C10, and D10 where picric acid solution and Cyanogas + naphthalene were used. On none of the plots were nematodes completely controlled. Where control was best the plants were

TABLE 5.—Yield of Lettuce per Plot and Tomatoes per Plant in Experiment of 1926

Plot	Treatment	Series A			Series B		
		Application per acre	Lettuce	Tomatoes	Application per acre	Lettuce	Tomatoes
		Lb.	*Oz.*	*Oz.*	*Lb.*	*Oz.*	*Oz.*
1	Check........................	....	159	68.7	....	137	76.4
2	Nicotine dust (2%)...........	870	134	79.2	2,150	174	70.1
3	Nicotine dust................ Sulfur dust..................	2,150 1,075	153	63.3	1,075 2,150	185	68.2
4	Check........................	....	165	60.7	....	181	85.8
5	Nicotine dust............... Sulfur dust.......... ... Paracide................	870 870 870	12	44.3	1,300 1,300 1,300	....	53.6
6	Sulfur dust...... ... . Acid lead arsenate...........	2,150 1,075	140	60.1	1,075 2,150	140	69.8
7	Acid lead arsenate...........	1,075	158	56.1	2,150	126	49.8
8	Cyanogas A grade..........	870	141	71.3	870	126	58.1
9	Check........................	....	162	63.1	....	189	76.0
10	Grasselli high grade phosphoric fertilizer	1,075	195	62.6	2,150	149	87.0
11	Grasselli fertilizer + barium silico fluoride......	1,075	185	65.1	2,150	200	95.1
12	Hydrogen silico fluoride	1,075	167	68.4	2,150	148	76.3
13	Fertilizer 2-8-10	1,075	161	62.8	2,150	168	81.6
14	Check	....	201	68.7	....	192	87.4
		Series C			Series D		
1	Check...........	....	144	59.4	....	116	65.6
2	Bi-product Grasselli, mostly sodium hyposulfate........	870	130	64.6	1,300	125	58.0
3	Sulfur dust..........	1,300	113	66.3	2,600	104	65.6
4	Tobacco stems, forked under.	20 T.	116	55.6	40 T.	115	53.9
5	Carbon disulfide.............	110 gal.	124	81.5	220 gal.	96	34.6
6	Check........	....	145	69.4	....	147	51.9
7	Saturated solution picric acid (.5%)..........	22,000 gal.	86	65.0	22,000 gal. +Ca(ClO$_2$)$_2$ 870	....	26.3
8	....	1,740 Liq. cresol	80	67.3	2,150 Ca(ClO$_2$)$_2$	99	23.0
9	Check........................	....	112	63.4	....	132	53.5
10	Naphthalene flakes .... Cyanogas (G grade).	870 870	88	82.0	1,740 1,740	80	88.4
11	Check.......................	....	130	76.1	....	169	69.5
12	Sodium silico fluoride.........	1,075	128	75.2	2,150	153	60.8
13	Dry lime-sulfur..............	1,075	160	75.4	2,150	145	59.4
14	Check...............	. ...	206	64.0	....	208	74.3

distinctly injured and the yield in some cases reduced. The compounds causing the most marked injury were cresol, picric acid + calcium hypochlorite, Paracide, Cyanogas + naphthalene, picric acid alone, and Cyanogas alone. This work strongly indicates, therefore, that these materials would be impractical where steaming is at all possible. One of the greatest difficulties, especially in a heavy soil, is that of getting an intimate mixture of the nemacide with the soil. Adequate preparation of the soil to the required depth will be a problem in itself even when the right chemical and proper dosage have been discovered.

In recent trials in New York, growers have used Cyanogas with a certain amount of success by making holes in the soil 8 to 10 inches deep at intervals of 6 inches each way and dropping in a teaspoonful of the fumigant.[2] This would require approximately one ton per acre, which at $25 per 100 pounds makes the cost of treatment by this method rather expensive. It would seem to be justifiable only in houses where steaming is not possible. In this connection recent work of Jones (18) is important. He reports that single applications of calcium cyanide were not always effective even when nearly five tons per acre was applied, but that three applications of 1200 pounds each made at weekly intervals killed all stages of the nematode. This treatment, he says, did not work in the hot dry summer months. In view of the expense and because August is a popular month for soil sterilization with many growers, the method is not wholly satisfactory.

CUCUMBERS

In order to test some materials that were not available at the time of the major plot experiments, a single series of plots was laid out in the Rocky River greenhouse. The soil was a heavy clay loam and heavily infested. It was plowed and spaded, barriers were sunk around each plot, and on July 12 the chemicals were applied. After an interval of 12 days, 5-day-old cucumber plants, grown in sterilized soil, were set in the plots. Chloropicrin in liquid form, being only slightly soluble in water, was poured into a gallon of 50 percent alcohol and applied to the soil by means of a watering pot. A 10-inch trench was dug and the chemicals were applied to its sides, after which the soil from the next trench was thrown into the first. The operator used a gas mask while applying the chloropicrin. Several of the cucumber plants were killed by the chloropicrin a few days after they were set; these were replaced.

[2]Letter December 1929 from Professor Chas. C. Chupp of the New York State College of Agriculture.

An extra row of cucumbers, to be pulled for examination, was set across each plot. None of the treatments gave very satisfactory control, altho there were fewest galls on the plot treated with Cyanogas.

"FERTAPS" AND "ZOTOKOS" AS NEMACIDES

An experiment to test the worth of "Fertaps" and "Zotokos" as nemacides and as plant "tonics" was carried on by M. L. Ruetenik. For three years one section of his house, 110 by 30 feet in area, received no steam sterilization but was treated with "Fertaps" and "Zotokos" according to the directions of the manufacturer. It is claimed that the effect of these materials is cumulative and consequently only a long test could be a fair one. During the third season yield data were obtained by the author from this plot and from a steamed area of equal size next to it. The results show that as nemacides and as "tonics" these materials are worthless. Neither "Fertaps" nor "Zotokos" controlled nematodes to any extent. The cost was $40 per application for these chemical treatments while an equal area was regularly steamed for a little under $20.

There were 27 pickings in all and 112 plants in each plot. The plants in the chemically treated plot acted characteristically for those of any heavily infested nematode soil. The vines were somewhat stunted and their fruits matured earlier. For the first 12 daily pickings the chemical plot yielded a greater total weight and a greater number of firsts. Thereafter, the steamed plot yielded more and, during the last two weeks of the season, practically twice as many tomatoes were harvested at each picking. The season's total yield was 15 percent greater from the steamed plot. The chemical plot yielded 7 percent more "small" tomatoes, under 2 inches, but the steamed plot yielded more seconds or rough fruit. Figuring the increased yield of 8 ounces per plant due to steaming at 10 cents per pound, an acre of tomatoes on sterilized soil would bring $750 more than an acre treated with "Fertaps" and "Zotokos". When the difference in cost of treatment is also considered there was a loss of several hundred dollars per acre from substituting "Fertaps" and "Zotokos" for steaming.

Besides this experiment, at least five other single plot tests in different greenhouses have come under the authors' supervision. In none of them have either "Fertaps" or "Zotokos", or both, shown any ability to control nematodes or any other plant ailment.

THE IDEAL NEMACIDE

A perfect nemacide should possess a combination of qualities not found in any of the materials tried thus far. It should be (1) effective in killing all stages of the nematode; (2) cheap enough to compete with steam; (3) harmless to vegetation or transient enough to cause no injury; (4) easy to apply, not prone to cake or absorb moisture; and (5) non-injurious to the man applying it. So far, the authors have not found any chemical that meets these requirements.

CHEMICAL TREATMENTS AND STEAM STERILIZATION COMPARED

The yields obtained from the use of the four best chemicals and from pan steam sterilization are given in Table 6. Fourteen pickings from six steamed plots are compared with a like number from four check plots and four chemically treated plots. The vines on the steamed plots were much more vigorous, taller, remained green longer, and produced larger fruits. Plot D10 treated with

TABLE 6.—Comparison Between Steam Sterilization and Four Best Chemical Treatments, 14 pickings

Plot	Treatment	Yields per plant				
		Firsts	Others	Total	Firsts	Total
		No.	*No.*	*No.*	*Oz.*	*Oz.*
S1	Steamed 50 minutes with pan........	13.9	4.3	18.2	73.5	91.0
D1	Check, no treatment..................	10.7	1.6	12.3	53.6	61.6
S2	Steamed 50 minutes with pan........	12.8	3.8	16.6	67.7	84.5
S3	Steamed 50 minutes with pan........	14.8	4.1	18.9	76.6	90.9
D6	Check, no treatment........	7.9	5.1	13.0	32.9	48.6
S4	Steamed 50 minutes with pan........	13.7	2.9	16.6	69.1	80.2
S5	Steamed 50 minutes with pan.	10.7	3.2	13.8	65.0	70.5
D9	Check, no treatment..................	8.0	5.0	13.0	37.0	47.4
S6	Steamed 50 minutes with pan........	10.8	4.0	15.0	61.2	63.3
D14	Check, no treatment..................	11.2	3.8	15.0	53.0	65.3
	Average of 6 steamed plots...	12.7	3.7	16.5	68.8	80.1
	Average of 4 checks...	11.3	3.5	14.0	44.1	55.7
D10	Naphthalene flakes 1740 lb. + Cyanogas (G) 1740 lbs.............	15.5	3.2	18.7	76.5	84.5
C5	Carbon disulfide 870 liters (110 gal.) p. a.	12.6	6.0	18.6	61.5	76.4
B11	Gr. fertilizers + barium silico fluoride 2150 lb. p. a.	13.5	5.4	18.9	60.8	75.5
C10	Naphthalene flake 870 lb. + Cyanogas (G) 870 lb...............	12.2	4.8	17.0	59.0	73.4

the larger amounts of naphthalene plus Cyanogas yielded considerably more than any of the other chemical plots. The plants on this plot maintained a vigorous growth, had a good color, and at the close of the experiment would have continued to set fruit had they not been topped back at the eighth cluster. This plot, however, did not yield as much as some of the steamed plots.

It is concluded from these experiments that, altho Cyanogas plus naphthalene in the higher quantities employed on Plot D10 greatly reduced the nematode population, better control was obtained at a lower cost with steam and, since methods of applying the chemicals are very much less satisfactory than modern methods of applying steam, it is unwise for growers to rely on chemicals if they can possibly use steam.

The six steamed plots averaged 24.4 ounces more fruit per plant than the untreated check plots. At an average price of 10 cents per pound, an acre of only 10,000 plants on steamed ground would have brought $1800 more than the same number on unsteamed ground. Subtracting the cost of steaming, a net gain per acre of $1500 was realized for soil sterilization.

Steam for Controlling Nematodes in Ohio

HISTORICAL

The application of heat to soils to make them more productive is a very ancient practice. Even the Romans observed that the productiveness of soils over which fires had been built was increased. The Italian writers of the latter part of the 19th century commonly advocated burning-over tobacco seed beds to rid the soil of the fungus *Thielavia basicola,* the cause of root rot. This was also a common practice among tobacco growers of southern Ohio during the last century.

The first use of steam for soil sterilization appears to have been by W. N. Rudd, of Greenwood, Illinois (26). In 1893 he was using a large bin 20 by 6 feet and 4½ feet deep with three perforated steam pipes in the bottom. The steam applied was allowed to escape thru 3/16-inch holes bored at 18-inch intervals. The bin was covered with hotbed sash, and a few potatoes on top of the soil indicated when the cooking was completed. A very similar system was used by a Mr. Lodder in Ohio in 1896. This system, slightly modified, is employed with success in some of the largest and most modern greenhouses where soil from the bins is sterilized in the headhouse before being placed in flats (Fig. 5).

BURIED-PIPE SYSTEM OF SOIL STERILIZATION

This method is now commonly employed by growers at Ashtabula and elsewhere. It is similar in principle to the old Rudd system and may have been an outgrowth from it. Instead of carrying the soil to the pipes, however, the pipes are carried about from place to place in the greenhouse and buried in the permanent beds where steam is liberated for 1 to 2½ hours. There is considerable leeway permissible in the specifications of a successful pipe system of sterilization. The pipes are usually 1¼ to 2 inches in diameter and vary in length from 35 to 150 feet. Holes 1/8 to

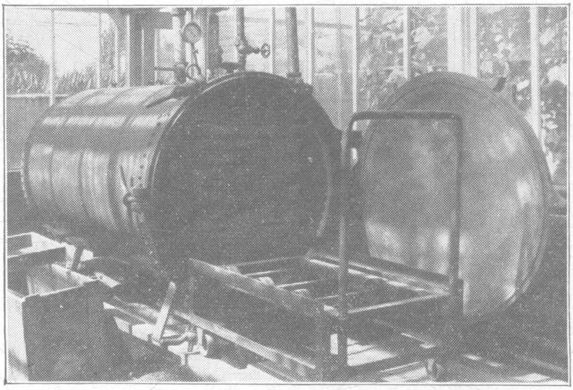

Fig. 5.—Modern type of pressure steamer now used at the Ohio Agricultural Experiment Station to sterilize flats and potting soil to eliminate nematodes and the pathogenes of wilt, damping off, mosaics, and root rots. (Courtesy of I. C. Hoffman).

3/16 inch in diameter are bored at 12- to 16-inch intervals and the pipes are laid from 6 to 12 inches deep, and 12 to 18 inches apart, according to their depth and the kind of soil. The deeper they are laid, the farther apart they may be, for example, 7 or 8 inches deep by 12 inches apart; 10 to 12 inches deep by 15 to 18 inches apart. In Colorado, Sackett (27) recommends that they be laid 24 inches apart. But this requires a longer steaming period. The laying is done by a crew of 3 to 15 men, who dig a trench or plow a furrow, lay the first pipe, and cover it while digging the next trench, and thus proceed across the house. A 17-foot house without posts then requires 2 sets of either 7 or 8 pipe lines spaced 15 to 12 inches apart (Fig. 6A). One end of each pipe is bent to protrude from the ground a foot or two and is provided with a union by which it is attached to a cross header, usually $2\frac{1}{2}$ to 3 incnes in diameter. After all the pipes are in place the cross header is attached. Where pipes more than 80 feet long are buried they should taper from 2 inches at one end to $1\frac{1}{4}$ inches at the other. It is important to

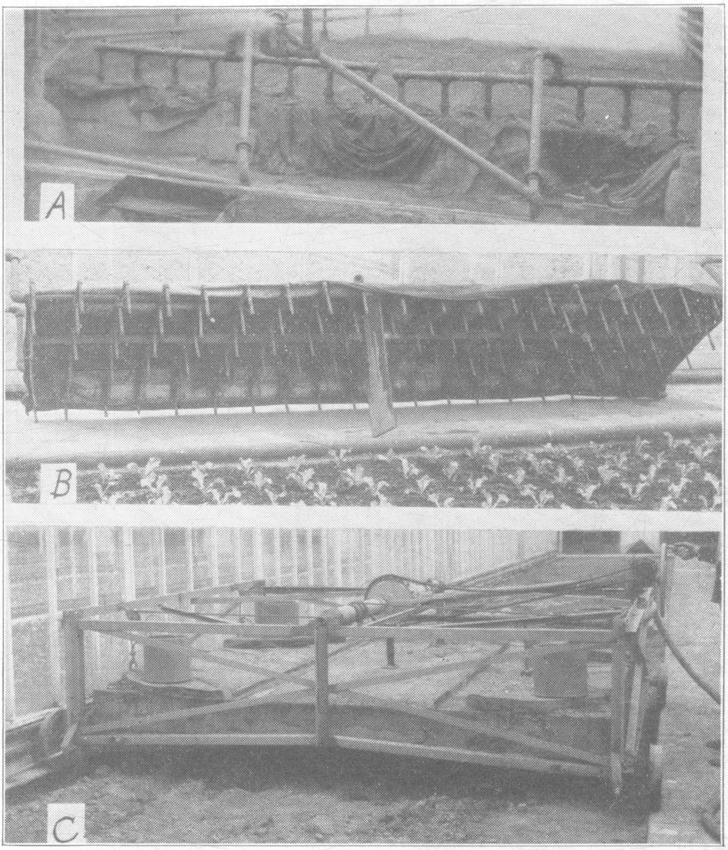

Fig. 6.—Three types of sterilizing equipment

A. A satisfactory buried-pipe outfit. B. The harrow assembly, a type which has practically disappeared from Ohio. C. The Miller Brother's one-man, under-slung pan in use at Toledo, Ohio.

blow out the holes in each pipe line as it is set in place, making sure that none are clogged. Usually one header supplies steam to but one set of 7 or 8 pipes. It is generally on the end, tho it may be in the middle, of the set. If either the header or pipe leading to it is too small the efficiency of the buried pipes is reduced.

As the steam is being admitted, the surface of the soil under treatment is covered with a tarpaulin, burlap sacks, old carpet, canvas, or heavy building paper to confine the steam and provide some insulation. If two sets are employed the crew may be kept fairly busy digging up and resetting one while the other is in use. It requires 10 to 20 minutes for four to six men to lift a set of 8 pipes 40 feet long, and 40 to 60 minutes to reset them in a new position. A horse and chain may be employed to drag the pipes, one by one, to their new trenches. In this way there is less trampling of the freshly sterilized soil and a crew of four men can make a change in less than an hour, if pipes are buried only 9 inches.

TABLE 7.—Temperatures Obtained With Buried-pipe Method After 1 Hour in Sandy Soil. Pipes Buried 8 to 9 in.; Boiler h. p. 100; Steam Pressure 45 lb.; Area 340 sq. ft.; Soil Temperature 52° to 57° F., at Beginning

Depth	In the vertical plane of a pipe				Between two pipes			
In.	*°F.*	*°F.*	*°F.*	*°F.*	*°F.*	*°F.*	*°F.*	*°F.*
7	205	200	210	205	205	210	210	200
8	200	190	205	195	195	200	190	185
9	180	150	200	190	160	170	155	140
10	140	120	150	130	125	130	120	115

The buried-pipe method has certain advantages and disadvantages. It combines the efficiency of the buried-tile method with low cost for equipment. In shovelling the soil over, it becomes very loose, permitting excellent penetration of the steam to all points in a minimum of time. Temperatures as high as 155° F. at 18-inch depths have been obtained after steaming for 2¼ hours. Usually 1 hour is sufficient with good steam pressure when the soil is fairly dry and all holes in the pipes are open. As with other methods commonly in use, temperatures of 140 to 150° F., are obtained down only as far as the soil has been loosened. Very little penetration into hard subsoil is to be expected even after a 2-hour treatment. See Tables 7 and 8 for some of the temperatures obtained in tests of this method.

TABLE 8.—Temperatures Obtained by Buried-Pipe Method of Soil Sterilization After 2 Hours. Pipes 15 in. Apart, Buried 12 to 16 Inches. Boiler h. p. 190. Steam at 60 lb. Pressure. Area Steamed 1,225 sq. ft. Soil Previously Dried for 7 Weeks. Soil Temperature 58° to 62° F., at the Start

Depth	In the vertical plane of a pipe		Between two pipes		Other isolated tests	
Inches	*°F.*	*°F.*	*°F.*	*°F.*	*°F.*	*°F.*
10	205	208	205	190	....	....
13	190	180	185	185	....	....
16	164	190	145	150	140	70
18	155	140	105	95	155	70
19	130	130	....	....	130	70

Because of the amount of soil that must be handled, the buried-pipe method is exceedingly laborious. There is also abundant opportunity for re-infestation while prying out the pipes. Success depends chiefly on two factors, (1) having all holes in pipes free from dirt and (2) using steam hot enough and for a sufficient time to obtain good penetration. As with every system of steam sterilization it is possible to find spots that are not thoroly heated, usually near a clogged steam outlet or in a very wet or hard soil.

Costs incident to the buried-pipe method are comparatively low, considering the depth of sterilization. A layout suitable for a boiler capacity of 450 h. p. may consist of seven 2-inch pipes, 85 feet long, fed by a 3-inch header. This equipment costs $145. Two such outfits together with the necessary leads, requiring 150 feet of 3-inch pipe for a house 200 feet long, brings the total cost to $335. With this equipment an area of 750 square feet may be steamed at one time to a depth of 10 to 18 inches in 1 to 2¼ hours. One may prefer to use a smaller unit for a smaller boiler. A convenient unit for a 100 h. p. boiler consists of seven 1½-inch pipes 40 feet long, fed by a 2-inch header 8 feet long. The cost of two such sets, each of which will steam an area of 330 square feet in 1 hour is $150. If sufficient 2½-inch pipe for a main thru a house 200 feet long is added, the total cost reaches about $210, which is comparable to a pan outfit covering a similar area. The pipe method sterilizes 3 to 8 inches deeper than the pan in the same or a little longer time, but requires considerably more labor. Where shallower sterilization, comparable to that done with the pan, is accomplished the coal consumed is about the same as in the pan system. Where more time is taken for deeper sterilization comparable to the buried tile method, the coal consumed is fully as much as with the tile method.

THE HARROW METHOD

The low cost and ease of operation make the harrow method (Fig. 6B) desirable, but this method gives unsatisfactory results in the elimination of nematodes, and is therefore no longer recommended. In Ohio there are only three or four places where it is being employed, and nematodes are not present in any of these houses.

Where the only pests to be fought are damping-off fungi, mosaic, weeds, and lettuce drop, the harrow system may serve the purpose. Unless a high pressure is maintained water condenses, clogs the spikes, and causes puddling of the soil, particularly in heavy soils. The steam tends to escape back along the spikes instead of penetrating laterally. If the steam is not turned entirely off while the harrow is being shifted to a new position, the spikes clog and inefficient steaming will result. Tables 9 and 10 give the temperatures obtained in sandy loam and heavy clay soils with the harrow. Table 11 gives a detailed comparison of the equipment and coal consumption of the harrow and the buried pipe methods.

TABLE 9.—Temperatures After 25 Minutes of Steaming With the Harrow in a Dry Sandy Loam Soil Plowed Twice. Boiler h. p. 150. Steam at 50 lb. Pressure. Area Steamed 75 sq. ft. Soil Dried 8 Weeks

Depth	Temperature of soil at different spots between the holes made by the harrow teeth								
Inches	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*
Harrow No. 1									
3	210	208	210	206	205	180	200	80	90
6	185	210	205	205	195	175	115	65	70
Harrow No. 2									
3	98	145	210	205	155	208	205	195	....
6	65	100	205	195	100	200	200	160	......
9	65	85	190	185	80	186	165	145	....
10	65	75	162	120	70	175	158	122	....
Harrow No. 3									
6	205	210	165	210	205	200	140	210	....
9	200	202	100	94	160	180	100	205	....
10	170	164	88	70	126	130	82	200	....
11	136	135	68	65	100	120	70	170	....
12	....	....	....	....	....	....	....	138	....

From Table 9 it is evident that, even under fairly favorable conditions of soil and steam pressure and with reasonable care in handling the outfit, a harrow does not give uniformly satisfactory results even at 3 inches, if we consider 150° F., as the necessary minimum temperature. In each of the three areas tested there were cold spots due to clogged spikes. Leaving the harrow in place for a longer time did not always remedy this defect as the following test, Table 10, on a heavier soil indicates. In a short time the steam found avenues of escape so that further steaming did not extend its penetration into the soil. A harrow for use in New Zealand greenhouses has six 9-inch hollow teeth per square foot instead of three

TABLE 10.—Some Temperatures Obtained With Steam Harrow in Moist Heavy Clay. Boiler 150 h. p. Steam at 35 lb. Pressure. Temperatures Taken at 6-inch Intervals and at a Depth of 6 Inches

	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	Av. ° F.
Temperatures after steaming 1½ hours	140	120	200	155	155	200	110	185	115	153
Temperatures after steaming 2½ hours	130 205	160 200	125 205	180 140	140 135	115 180	110 160	185 130	210 150	158

TABLE 11.—Buried Perforated Pipe* and Harrow† Methods, Showing Areas Steamed per h. p. and Coal Consumption

Greenhouse name	Method	Boiler power available	Steamed at one time	Time per unit	Boiler gauge pressure	Steamed per h. p.	Coal used per acre	Coal used per sq. ft.
		H. p.	*Sq. ft.*	*Hr.*	*Lb.*	*Sq. ft.*	*T.*	*Lb.*
Dunbar	Pipe	300	935	1½	100	3.1	80	3.67
Gallup	Pipe	150	1200	1½	90	8.0	75	3.40
Griswold	Pipe	190	1224	2¼	60	6.4	100	4.59
Ingles	Pipe	450	765	1	70	1.7	....	....
W. Reserve	Pipe	100	330	1	50	3.3	30	1.37
Riverside	Pipe	200	250	1	50	1.25	50	2.27
James	Harrow	150	250	2	40	1.65	50	2.27
Ohio	Harrow	3@75	96	½	50	.43	25	1.13
Searles	Harrow	225	190	¼	80	.84	30	1.37

*A temperature of 150° F. can be obtained 9 to 18 inches deep with the buried pipe method depending on depth of burial and duration of steaming period.

†A temperature of 150° F. can not be depended on with the harrow, even to a depth of only 6 inches. The cost varies between 0.7 and 2.3 cents per square foot, and by the buried-pipe method approximately 3 square feet per h. p. per hour can be steamed.

7-inch teeth as used in Ohio. It is claimed for it that killing temperatures are obtained at 8 inches in a few minutes, but no data on nematode control are at hand (1).

THE PAN SYSTEM

DESCRIPTION OF EQUIPMENT

The steam-pan, like the buried-pipe method, originated independently in more than one part of the country. It is said to have been first used by Shamel of the U. S. Department of Agriculture, in 1904 in Connecticut to sterilize outdoor tobacco seed-beds. However, the idea seems to have originated independently with the Wutrick Brothers, Brooklyn Station, Cleveland, Ohio, who claim to have tried it with success in the late nineties. It was in fairly general use among growers of that neighborhood by 1904. It has been widely adopted and modified and improved by greenhouse men for nematode control in northern Ohio greenhouses.

The apparatus consists of a rectangular galvanized iron pan from 6 to 9 inches deep. The pan is inverted over the soil and steam is admitted under pressure. The size and shape of the pan may vary with the width of the greenhouse and position of purlin supports. The smallest pan coming under our observation was 5 by 6 feet, covering 30 square feet of soil. The largest covered 112 square feet. Probably the most common size for use in a 30-foot house is 7¼ by 10 feet. A set of four such pans covers the entire width of the house and steams 300 square feet at a time

(Fig. 7). The pans are usually made of 20- or 22-gauge galvanized iron. Sometimes heavier material is used for the sides than for the top. With 20-gauge or lighter the rim should be reinforced with a thin piece of strap iron, leaving the edge as sharp as possible so that it can be forced into the ground. If 14-gauge is used for the sides extra reenforcing will not be needed. Suitable reenforcement of the pan with two-by-fours, angle irons, or pieces of gas-pipe must be provided to insure rigidity. Handles are fastened on the two ends of smaller pans and at the four corners of larger, heavier ones. A notch is left in one side to permit entrance of the steam pipe, or a 1¼-inch pipe is built into the pan with suitable union on the outside for connection with a flexible steam hose.

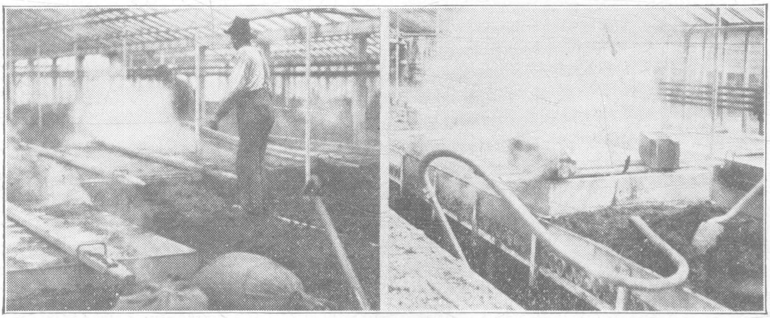

Fig. 7.—The inverted pan system in operation

The weight of such a pan varies from 300 to 500 pounds. Larger pans are heavier and are lifted by pulleys. A heavy pan is preferable to a light one, since steam under higher pressure to secure deeper penetration can be used without its lifting the pan off the ground. Weights such as concrete blocks, sacks of sand, or pieces of steel rail, are usually placed on the corners of the pan and soil is banked around the sides to help force the steam into the ground.

COST OF STEAM PAN EQUIPMENT

For steaming a house 30 by 200 feet, the approximate cost of the equipment shown in Figure 8 is as follows:

4 pans at $25 to $40 each	$100 to $160
Assembly No. 1	250
Assembly No. 2	225
Assembly No. 3	280
Assembly No. 4	310 to 330

The No. 1 assembly requires a minimum of time to set up, is convenient to operate, and delivers the hottest possible steam to the pans. The 2½-inch lead may be suspended in the air or, as in the other assemblies, it may rest on the ground. In No. 2, plugs are arranged in the leads at 10-foot intervals, one being removed at each new pan position to permit attaching a tee with a short delivery pipe going into a pan on each side. The longer the leads the more condensate reaches the pans, and the wetter the soil the poorer the penetration. Leads of 1¼ inches serve well in a small house, 100 feet long, while 2-inch pipes should be used in very long

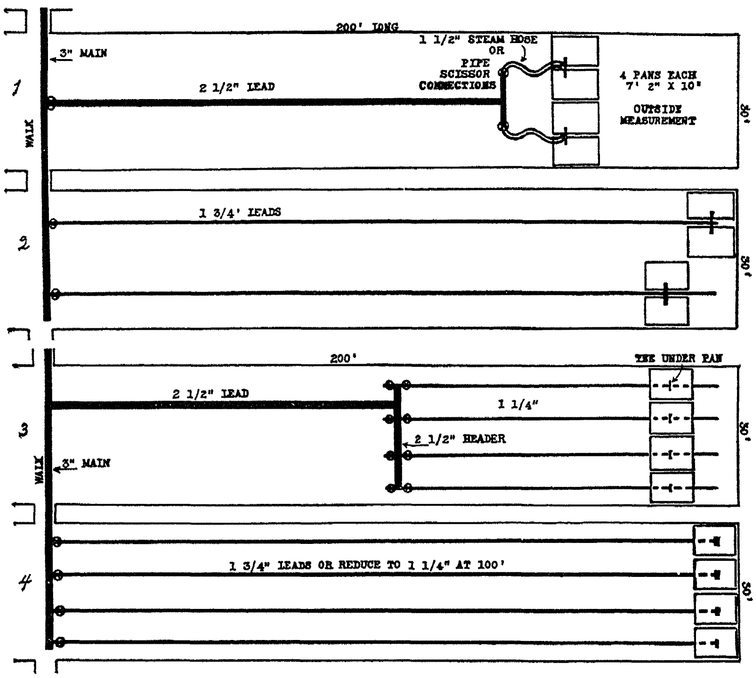

Fig. 8.—Diagram of four assemblies for the inverted pan method

houses. These leads may taper to 1¼ inches at the far end. The third type of equipment probably delivers steam efficiently to the pans in a long house. Each pan may be moved independently of the others. This is of advantage, especially if the soil is wetter on one side of the house than on the other. This assembly can be cheapened some $50 by the use of two secondary leads instead of four. The fourth assembly is the most expensive, but is not necessarily the best. Each pan can be moved independently but larger heat losses occur in this system and wetter steam reaches the pans.

Nos. 1 and 3 are the best for a long house. The first may be cheapened by using scissor-pipe connections in place of steam hose (Fig. 6A). The other may also be cheapened by using two secondary leads in place of four. The pans will last from two to six years. The pipes should last 10 years or longer with ordinary care. While galvanized pipe is preferred by most growers, black iron pipe gives good service and is cheaper.

CERTAIN IMPROVED PAN OUTFITS

The Thompson Rolling Pan

Figures 9, 10, and 6C indicate how three Ohio growers have improved the pan system. In the first, R. S. Thompson, Bay Village, Ohio, overcame the necessity of stepping on the freshly sterilized soil when lifting the pan, by building a pan that can be rolled over into its new position. It is really three pans in one and looks like a big hollow 3-sided prism. A small block and tackle enables one man to handle the pan. A 3-way 1¼-inch pipe inside

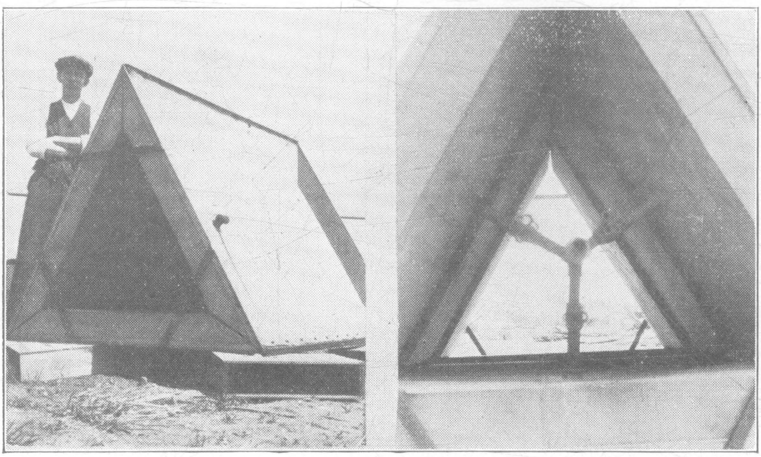

Fig. 9.—The Thompson one-man rolling pan

the prism with a valve on each arm and a single union at the center for attachment to a flexible steam hose enables the operator to turn the steam off and on as desired. The sides of the pans are of 20-gauge and their backs of 24-gauge galvanized iron. The edges are lined with strap iron and the pans are fully braced with strap and angle irons at the corners and inside.

The Darrow Hanging Pan

Another ingenious time- and labor-saving improvement was made by the Darrow Brothers, Poland, Ohio. Their three pans are each 15 by 7½ feet, and 8 inches deep, enabling them to steam 300 square feet at one operation with a 6-inch lapover. The sides are of 14-gauge and the tops of 22-gauge galvanized iron. Sides and tops are braced by five 1½-inch pipes across the top on which two 15-foot railroad rails are laid to give additional weight (Fig. 10).

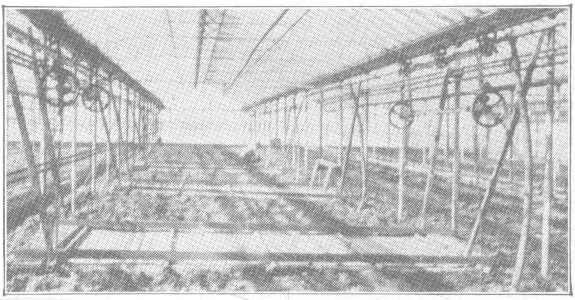

Fig. 10.—The Darrow hanging pan

The pans are lifted by a crank and chains, suspended from hay track hangers that operate on angle iron hay tracks temporarily hung under the gutters and extending from end to end of the house. With three pans operating simultaneously one can be changed every 20 minutes. With a 2½-inch lead instead of the 2-inch now in use 50 percent more steam could be delivered to the pans. Four pans could then be operated at once with ease, covering 450 square feet per hour with one boiler of 150 h. p., maintaining 80 pounds pressure. The steaming of an acre, now done in about 140 hours, could be done in 98 hours.

The Miller One-Man Underslung Pan

A third pan improvement of merit in saving time and labor is that developed by the Miller Brothers, Toledo, Ohio. It consists of a heavy pan 8 by 12 feet, suspended on a steel frame all of which is mounted on four wheels running on the edge of the concrete walk bordering the beds, their houses being only 12¾ feet wide. This pan is elevated and lowered by a crank. The operator winds or unwinds four ropes on a drum in the center of the supporting frame (Fig. 6C). The crank is on the side so that the operator remains on the concrete walk, never stepping on the sterilized soil. The simplicity of operation enables one man to look after two pans in the daytime. At night the fireman may take care of one and thus the labor cost for steaming be reduced. Two 330-foot houses can be steamed in 24 hours when the pans are in place 30 minutes. In this way an acre is done in less than six days. The area steamed with two pans is only 190 square feet and, since 90 pounds pressure is maintained with ease on their 150 h. p. boiler, probably two or three times this number of pans could be operated at once. Since lettuce is their chief crop and nematodes are absent, Miller Brothers do not find it necessary to sterilize deep. It is more satisfactory to give the soil a shallow steaming at intervals of 6 months.

TEMPERATURE OBTAINABLE WITH PAN SYSTEM

The pan system, as commonly employed in Ohio, is less effective than either buried tile or buried perforated pipe, which will be discussed later. However, killing temperatures are obtained much deeper with the pan than with the harrow, and under similar conditions the pan is much more reliable. Table 12 summarizes some of the results obtained in a number of commercial houses near Cleveland. The temperatures were recorded with a dairy thermometer immediately after removing the pan. As with other systems tested, a variation of 40 degrees F. was sometimes found

TABLE 12.—Temperatures Obtained by the Pan System of Soil Sterilization

Depth	Temperature, degrees Fahrenheit								
Test 1—Hinckly, dry sandy loam, 26 percent moisture, after 1 hour steaming, 50 lb. pressure									
5	205	210	212	210	210	160*	200	......	......
10	175	175	195	145	140	90*	140	......	......
Test 2—Cuyahoga, moist clay loam, after ¾ hour steaming, 90 lb. pressure									
5	212	190	160*	180	......	......	......	......	......
7	205	140	85	120	......	......	......	......	......
9	190	100	70	90	......	......	......	......	......
11	145	70	65	70	......	......	......	......	......
Test 3—C. James, very moist (50%) heavy clay, after 1½ hours 75 lb. pressure									
6	200	205	195	150	165	165	190	150	145
7	180	190	180	120	140	143	170	120	118
8	165	180	165	100	105	95	160	85	80
Test 4—Cleveland City Farms, very dry, loose gravelly loam, after 1 hour 90 lb. pressure									
5	206	204	204	202	......	......	......	......	......
7	206	204	200	200	......	......	......	......	......
9	190	204	190	170	......	......	......	......	......
11	160	195	160	140	......	......	......	......	......
12	140	175	140	100	......	......	......	......	......
15	100	145	100	......	......	......	......	......	......

*Hard soil not sufficiently loosened.

between points at the same depth only a few inches apart. This variation was due to differences in compactness and moisture content of the soil.

In the following test (Table 13) made at C. James' greenhouse, Berea, Ohio, a pan and a harrow were employed simultaneously side by side on parallel lines of 1¼-inch steam pipe. The soil was a very heavy, wet clay, containing more than 50 percent moisture. Steam pressure on the boiler 70 feet away was maintained near 75 pounds. The temperatures were obtained after 1¼ hours and 2½ hours, respectively.

TABLE 13.—Soil Temperatures Under the Pan and Harrow Methods of Steaming on a Heavy Wet Clay Loam

Depth	A. After 1¼ hours				B. After 2½ hours			
	Pan		Harrow		Pan		Harrow	
	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*
6 inches	205 205 190	195 190 185	180 150 110	190 135 115	205 207 200	205 200 205	200 135 240	110 180 160

The harrow did not give killing temperatures in heavy wet clay at 6 inches; the pan was fairly effective.[3]

After making several hundred temperature tests in many commercial greenhouses, the authors believe that good sterilization is not ordinarily to be expected with the pan method below 6 to 8 inches. The pan method gives fairly satisfactory control of nematodes where only one high-temperature crop, such as tomatoes, is grown in the rotation, but if tomatoes and cucumbers are both included in the rotation the pan fails to kill at sufficient depths to protect both crops. Continued favorable soil temperature, in the course of 12 months, enables the few nemas left below 8 inches to multiply and greatly damage the second crop.

DURATION OF HEAT AFTER STEAMING

Temperatures below the third or fourth inch usually continue to rise after the steam has been turned off. A most accurate picture of the temperature changes in the first 7 inches of a spaded silt loam after a 40-minute period of steaming is given by Hunt, O'Donnell, and Marshall (17). They buried a number of electrical resistance bulbs under the pan and read the temperatures with a

[3]Killing temperatures are assumed to be close to the pasteurizing temperature of 150° F.

Wheatstone bridge, over a period of several hours. The pan was left on the soil for one-half hour after the steam was turned off. some of their data are given in Table 14. They state

> The table shows that in most cases the temperature began to fall at the 1-inch depth almost as soon as the steam was shut off. At the 4-inch level the temperature continued to rise for several minutes after steam was shut off, except where the 100° C. was reached before the steam was shut off. At the 7-inch level the temperature continued to rise for a considerable time after steam was shut off, except where a temperature of 100° had previously been reached. The temperatures at all depths usually became somewhat uniform within 4 hours after steam was turned on, regardless of whether steamed 25 or 40 minutes, the temperatures being somewhat higher than the initial temperatures.

This increase in temperature after the steam was turned off was not noted to any marked extent in our experiments even where the buried-tile method was employed.

TABLE 14.—Temperature Changes in Soil Under a Steam Pan During and After a 40-minute Steaming Period. Gauge Pressure 95 lb. on the ¾-inch Lead to Pan. Data From Hunt, O'Donnell, and Marshall (17)

Depth	Initial temperature of soil	Maximum temperature attained	Time to attain maximum	Temperatures at intervals after maximum had been reached					Average maximum sustained temp. for ½ hour	Sets averaged
				10 min.	20 min.	30 min.	45 min.	60 min.		
Inches	*°F.*	*°F.*	*Min.*	*°F.*	*°F.*	*°F.*	*°F.*	*°F.*	*°F.*	*No.*
1........	71	209	32	205	199	191	171	146	204	4
4........	68	166	54	160	159	157	150	146	160	5
7........	66	100	151	99	99	99	99	97	99	4

The authors state that even an 85-minute steaming with the pan under 95 pounds steam pressure is not always effective against *Synchytrium endobioticum*, causing potato wart, spores of which have been found 8 inches in the ground. It is evident that in the silt loam soil used in their experiments the pan could not be expected to give killing temperatures for nematode control as deep as 7 inches in 40 minutes; nor would it control tomato wilt.

Beinhart (2) reports temperatures from the pan method as follows:

> In sandy soils after 30 minutes of steaming, the temperature to be expected in the upper 2 inches of soil directly under the pan is 208° to 212° F., at 3 to 4 inches 170° to 180°, and at 6 inches 120°. Two hours after the removal of the pan the temperature at 6 inches should be about 160° F.

Observations made at Ashtabula indicate how long the soil remains hot after steaming with the buried pipes for 2¼ hours. At the end of the steaming period the average temperature 16 inches deep was 142°. Forty-eight hours later the temperature at this depth averaged 125°. In another house where a 2-hour steaming with buried tile had been given the soil, the temperature was 146° at a depth of 16 inches. After a lapse of 14 hours an average temperature of 151° was found at this depth.

Obviously several days should elapse before plants are set in steam sterilized soil and a thoro watering should be given them.

BURIED-TILE SYSTEM OF SOIL STERILIZATION

The importance of deep soil sterilization to kill nematodes and the tomato wilt fungus is emphasized by two facts: First, tomato roots harboring the wilt fungus (Fusarium) penetrate downward many feet; and second, nematodes have been found to inhabit not only the first but the second and third feet of soil in greenhouses. Killing temperatures have been obtained with the pan method to depths of 6 or 8 inches, and with the perforated pipe method to depths of 8 to 15 inches. But growers are turning more and more to the tile system of sterilization on account of the greater depth of penetration and the convenience in operation. There are two general systems, the temporary system and the permanent system.

TEMPORARY TILE SYSTEM

This method involves laying and steaming with 2 to 12 lines of tile at a time. Lines are removed as soon as sterilization is completed and the tile are cool enough to handle. They are then used over and over. The lines are usually laid 8 or 9 inches deep and 18 inches apart. A house 75 feet long by 16 feet wide should be laid by two men in a day and, while two lines are being steamed two hours at a time the second day, the men can tile the next house. A crew of five can sterilize a house 200 by 25 feet in this manner in five days with boiler capacity of 250 h. p. maintaining 80 pounds pressure.

Since temperatures of 145 to 160° F., have been obtained at depths of 17 inches after a 2-hour steaming with temporary tile, this would seem to be an efficient method with a low equipment expense, but the labor required is a large item. Since one man can lay about 450 tile 8 inches deep per day, the cost is about 1 cent per tile. The labor cost of laying an acre of tile lines 18 inches apart would amount to about $300. With an annual coal cost of another $300 this system becomes as expensive as the permanent system without being nearly as convenient.

PERMANENT TILE SYSTEM

In the permanent system the entire area to be steamed is tiled. Permanent headers and risers are installed, and everything is left in place for many years. Its only drawback is the first cost. When once installed it is easy to operate, fairly economical, and permits a more thoro job of steaming than any other method yet devised. Furthermore, the same lines of tile may be used for sub-irrigation and for leaching out soluble salts when these become troublesome.

Size of Tile

Both 3- and 4-inch tile have been used successfully for more than ten years in Ohio greenhouses. The 3-inch tiles seem to have the necessary capacity as long as they remain in line. The 4-inch have more joint area and, hence, may function even after considerable displacement. They were dug up and relaid in one large house after 12 years of service. Under high boiler pressure (125 pounds) 3-inch tiles in lines near the boiler sometimes have been split by the sudden admission of steam. The two sizes, however, have not been tried in the same house for a period long enough to prove their relative merits. The 4-inch size costs more and requires a little more labor to lay.

Depth and Distance Apart for Tile Lines

Several factors enter into the selection of the best depth and intervals for tile lines. It has been contended that sterilization, if done thoroly deep enough, would be required but once in two or more years; but the opportunities for reinfestation and the difficulties in sterilizing under the walks and in the corners render this policy unsafe. One case is on record at Toledo in which a grower sterilized thoroly with tile the first year that nematodes appeared; and for six years thereafter no sign of nematodes was seen. But most men wait until pests have become thoroly established before attempting control; under such conditions annual sterilization becomes necessary. It is economical, therefore, to sterilize to a depth of only 12 to 22 inches, which is sufficient to protect the crops in the succeeding twelve months. To protect cucumbers against nematodes and tomatoes against Fusarium wilt requires sterilizing to the greater depth, while lettuce, radish, and spinach troubles require only the lesser depth.

Tests at the Warrensville Greenhouse

Tests to determine cost of installing and efficiency of a permanent tile system in which the lines were laid 12, 18, and 24 inches apart were begun in the greenhouse of the Cleveland City Farms at the author's suggestion in 1928. With the cooperation of Mr. Starkey, manager of the farm, one of the ground beds 100 by 13 feet was divided into two equal plots. The northern half, 50 feet long, was tiled with lines of 3-inch tile laid 12 inches apart and 15 inches to the bottom of tile.[4] This plot is designated as section A. The south end of the bed, section B, was similarly tiled with lines laid 18 inches apart and 19 inches deep. As shown in Figure 11, one-half of the lines in each section were connected at the opposite end from the header one line having outlet to the sewer. This line

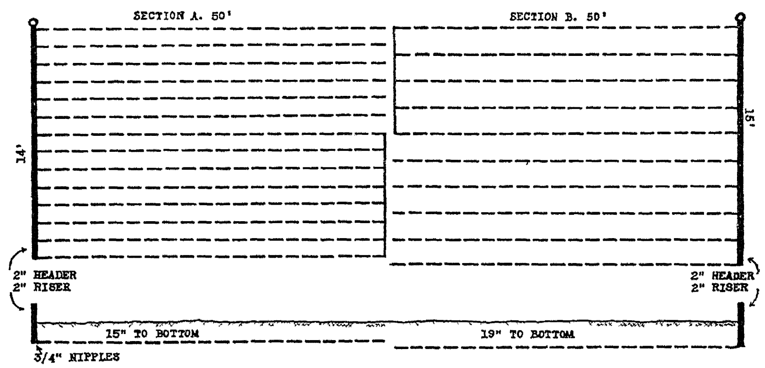

Fig. 11.—Diagram of assemblies for the buried-tile system in two sections of the Warrensville greenhouse

could be stopped up at will. In the course of several years some tile may become more or less clogged. If the lines are cross-connected at the far ends, steam may circulate and back into any clogged line. The headers were buried on a level with the tile and steam supplied to each line thru ¾-inch nipples 6 inches long. The space around the nipple inside each tile was filled with a little cement. The headers were 14 and 15 feet long, respectively. The one in section A supplied 14 lines of tile, two lines being placed under the 2-foot walk; the one in section B supplied 10 lines. About 675 feet of tile were laid in section A and 470 in section B. A year later a section C was laid with lines 24 inches apart and 20 inches deep. This section contained 340 feet of tile.

[4]Placing lines this close raises the level of the soil permanently about 2 inches. In section B it was raised about 1½ inches.

Highly satisfactory temperatures in sections A and B were obtained by steaming four hours. As would be expected, the surface layers were slower in attaining a high temperature in section B, in which the tile were deeper and in which penetration also was a little deeper. (Table 15).

TABLE 15.—Temperatures Obtained at the Warrensville Greenhouse With Buried Tile Lines Laid at Different Depths and Different Distances Apart. Boiler Pressure 110 Pounds, Pressure on Steam Line Near Header 30 Pounds

Time at which records were taken	Depth	Section A Lines 12 in. apart 15 in. deep	Section B Lines 18 in. apart 19 in. deep
	In.	°*F.**	°*F.**
After 2 hours of steaming	8	208	183
After 4 hours of steaming	21	165	180
	23	150	167
	25	140	155
	27	130	150
Two hours after 4 hours of steaming	22	....	184
	25	....	158
	27	....	138
	29	....	130

*Temperatures given are averages of several readings at each depth.

The 18-inch distance gave results as good as the 12-inch distance. This represented a considerable saving in the first cost of laying the tile (Table 16). Unfortunately, no data are yet available on section C. But tests at the Experiment Station greenhouses (Fig. 12) where lines are laid 12 inches deep and 22 inches apart indicate that very satisfactory sterilization may be secured at this distance if the duration of the steaming period is 6 or 8 hours

TABLE 16.—Principal Costs of Installing Buried Tile in Three Different Depths and Distances in 1/67 Acre

Depth	Distance apart	Total tile	Tile at $25 per thousand	Laying at 40 cents per hour	Headers and risers	Total cost per acre
Inches	*In.*	*No.*	*Dol.*	*Dol.*	*Dol.*	*Dol.*
11	12	675	16.77	6.75	10.00	2,245
15	18	470	11.75	6.11	9.50	1,831
18	24	340	8.50	5.44	9.00	1,536

(Table 17). Brown (5), after five years of trial, states that lines 3 feet apart and 12 to 14 inches deep to top of tile were not close enough to keep Fusarium wilt under control even with a 10- to 12-hour steaming period at 60 pounds pressure. Two feet apart is thought a better distance. At the Weiant Gardens of Newark, Ohio, tile lines laid 2 feet apart were not satisfactory and have been reset at 18 inches.

Tests in the Experiment Station Greenhouse

In the horticultural greenhouse of the Ohio Agricultural Experiment Station the tile lines are 22 inches apart and 12 inches deep (Fig. 12). Satisfactory results are usually obtained with 6 hours of steaming at 90 pounds pressure at the boilers, 300 feet away. In one portion of this house, where the tile are but 6 inches deep, Fusarium wilt is not always completely controlled. Table 17 shows the temperatures obtained in two of the beds.

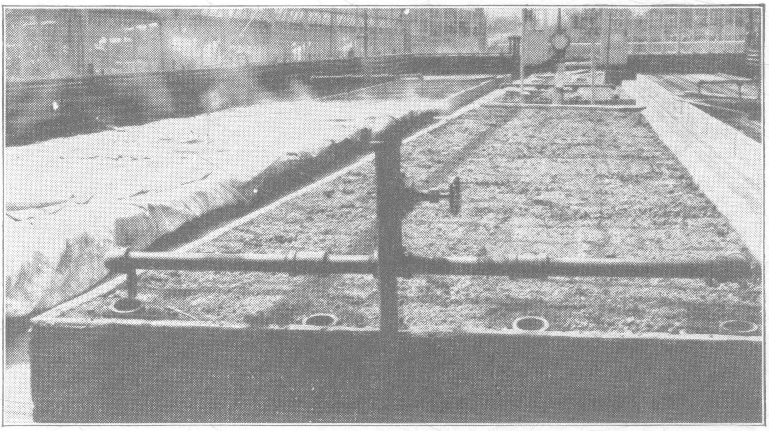

Fig. 12.—Buried-tile system in operation at the Ohio Agricultural Experiment Station

There was considerable difference between the temperatures obtained in two beds of different moisture content. At a 12-inch depth, after 2¼ hours of steaming in the dry bed the temperature averaged 179° F., while in the moist bed it averaged but 152°.

Costs of Tiling

The cost of laying three sections at the Warrensville house has been computed on the basis of 2½ cents per foot for tile, 40 cents per hour for labor, and a flat rate of $9 to $10 for the headers complete.

The costs in Table 16 do not include the expense of steam mains, secondary leads to the risers, flexible steam hose, scissors connections, valves, and other fittings, which would be the same for all three arrangements. The figures give the difference in cost of installing a system of lines at different widths and depths in an ordinary clay loam. In a sandy soil the cost of laying the tile might be lower and in a stiff clay higher. One grower, having such

TABLE 17.—Temperatures Obtained With the Tile System at the Experiment Station. Lines 22 in. Apart, 12 in. to Bottom, Boiler Pressure 90 lb.

Depth	Average temperature	
	After 2½ hours	After 9 hours
Inches	*°F.*	*°F.*
8	197	210
10	181	208
12	165	206
16	120	198
17	90	180
18	70	160
19	68	140

a clay, estimated the total cost of laying tile 14 inches apart and 15 inches deep in his ¼-acre house at $800, or $3,200 per acre. The average cost for tiling sometimes has been placed at $2,500 per acre. In many houses only half as many headers are used as in the Warrensville experiment. This would reduce the cost per acre $100 to $200. Brown, Baldwin, and Conner (6) found the cost of installing a complete tile system, in which the lines are 3 feet apart to be $1,400 per acre.

Much labor could be saved by laying the tile before building the greenhouse. A regular tile ditch-digging machine could then be used to dig the six miles of ditch required for an acre, at 18-inch intervals. But this procedure does not pay because soil sterilization is not usually necessary the first five years. A traction ditcher small enough for greenhouse use is needed and doubtless will be on the market in a short time.

Several greenhouses near Cleveland have eliminated a part of the hand labor of digging ditches in heavy clay by employing a tractor-drawn, mold board ditcher. The ditcher is drawn back and forth by a set of long cables from one end of a house to the other. It requires two or three trips to dig a ditch 14 inches deep, but when complete it is an even depth and straight, ready for a shallow layer of cinders or crushed limestone chips and the tile. Another 1-inch layer of cinders or chips is placed over the joints. A plow is then used in filling the ditch.

The author has recorded temperatures of 140° to 160° F., 22 inches deep in heavy clay loam several hours after an 8-hour steaming in one of these houses.

SHAPE AND SIZE OF UNIT AREAS

The shape of a bed does not seem to be a factor in steaming. It may be square or long and narrow. Beds 150 by 16 feet are successfully steamed. Beds of this size are in use where buried pipes are employed, the header directing steam 75 feet in both directions. The longest distance steam has been sent thru tile from a buried header with success, as far as we know, is 110 feet. Longer distances probably would give uneven sterilization. Likewise beds 40 feet wide are now being successfully steamed with one header in recent tile installations.

Until recently growers have used harrows or pans that covered a combined area of only 90 to 350 square feet per 100 h. p. boiler. This means steaming 0.9 to 3.5 square feet per horse power. Many who discontinued lettuce, the low temperature crop, found it necessary to sterilize deeper and so employed the buried-pipe method. With this system the maximum area per horse power seems to be 6 to 8 square feet. But, with the buried tile, several systems, which have been in use a number of years, have steamed 12 square feet per horse power. A few growers steam larger areas. One installation takes care of 2,400 square feet with a 100 h. p. boiler; another 16,000 square feet with a combined boiler capacity of 600 h. p. Such large areas per horse power require from 10 to 24 hours of steaming at a time. When a few tile are clogged it may take hours of steaming to find it out. Smaller areas may therefore be more economical of coal. Little trouble from clogging occurs the first two years.

The object in any system of steaming is to force the largest possible number of heat units into the soil in the shortest time with a minimum of coal. Obviously, with a given boiler capacity, doubling the area steamed doubles the time required to bring the soil to the desired temperature. Tables 18 and 19 give data on such items as boiler horse power, unit area steamed, and fuel used in a number of successful vegetable greenhouse assemblies.

TABLE 18.—The Pan Method,* Showing Area Steamed per h. p. and Coal Consumption per Square Foot of Soil Sterilized

Name	Total boiler power available	Area steamed at one time	Time to steam one unit	Boiler gauge pressure	Area steamed per h. p.	Coal used per	
						Acre	Sq. ft.
	H. p.	*Sq. ft.*	*Hr.*	*Lb.*	*Sq. ft.*	*T.*	*L.*
Cuyahoga	125	336	1	75	2.7	40	1.76
Darrow	150	336	1	80	2.2	....	....
Dreger	125	300	1	70	2.5	35	1.60
Hinckly	150	230	1	50	1.5	40	1.76
James	150	300	1¼	40	2.0	40	1.76
Miller	150	190	½	90	1.3	25	1.13
Ruetenick	100	360	1	90	3.6	27	1.24
Wagner	100	300	¾	50	3.0	50	2.28
Keyes	125	360	½	70–80	3.0	22	1.03
Wutrick	160	320	1	50	2.0	50	2.28
Heinrick	200	300	1	75	1.5	25	1.13
Asplin	100	140	50 min.	50	1.4	50	2.28

*In general this method gives a temperature of 150° F. to a depth of 5 to 10 inches. By it one can figure on sterilizing 2 square feet per hour per horse power at a cost of from 0.6 to 1.2 cents per square foot.

TABLE 19.—The Buried-tile Method as Employed in Several Greenhouses, Showing Variation in Area Steamed per h. p. and Coal Used

Greenhouse	Total boiler power	Area steamed at one time	Time per unit	Boiler pressure	Area steamed per h. p.	Coal per acre	Coal per sq. ft.
	H.p.	*Sq.ft.*	*Hr.*	*Lb.*	*Sq.ft.*	*T.*	*Lb.*
Adams*	250	270	2	70	1	80	3.67
Dean†	100	2,400	12	15	24	44	2.00
Goldwood	140	1,345	8	60	10	65	3.00
Ingles.	450	2,625	6	65	5	50	2.28
Joder	600	16,000	10—24	100	26	....	....
Luce*	250	500	1	90	2	90	4.10
Meyers†	125	780	4	80	6	45	2.05
Rockport†	300	3,300	8—12	80	11	55	2.53
R. River	400	1,200	4—6	100	3	71	3.20
Ruetenick†	100	1,500	6—8	80	12	60	2.75
Weiant†	360	1,125	3	125	3	89	4.00
Wright	300	2,062	6	125	6	....	....
Hoag	200	1,080	8	50	5	....	....

*These greenhouses use a temporary tile system; all others are permanent.
†These have a close estimate of coal burned.

With coal at $5 a ton, the cost of fuel varies between ½ and 1 cent per square foot. Interest on an investment of 6 cents a square foot amounts to ⅖ cent, and labor to ⅕ cent, making the total cost of steaming with tile between 1.1 and 1.6 cents per square foot. A temperature of 150° F., is readily obtained at depths of 12 to 24 inches by the permanent tile method, and one can figure on sterilizing 1 to 2 square feet per horse power per hour, at a total cost below 2 cents a square foot. When it is realized that practically twice as thoro a job is done by this method as by the pan, and at very little increase in cost, and that it eliminates the hard manual labor necessary in the buried-pipe method there is little doubt that it is the best method yet devised for controlling nematodes and Fusarium wilt in greenhouses.

LONGEVITY OF THE TILE SYSTEM

There are tile systems in Ohio that have been in operation for 17 years. One system, after 12 years of service, was reset recently; another, after 15 years of service, is in need of resetting. In none of these older systems was care taken to connect the distant ends of the lines or to surround the joints with anything but soil or to provide suitable drainage.

GENERAL DISCUSSION

WATER ADDED TO SOIL IN STEAMING

A meter test made at the Western Reserve greenhouse during three 1-hour steaming periods showed that an average of 1.8 gallons of water was vaporized for each square foot of soil steamed. Here the buried pipes were only 8 inches deep. In a second house where pans were used 1 gallon was vaporized per square foot.

In another test with tile 18 inches deep and the steaming period six hours, 3.6 gallons of water was used to each square foot.

A similar test in a fourth house, in a 3-hour period, required 4.7 gallons of water per square foot.

These quantities of water seem large, but a large portion escaped into the air as vapor and sank into the subsoil. Brown, Baldwin, and Conner (6) report more than 2 gallons used where the tile lines were 3 feet apart.

SOIL STERILIZATION WITH HOT WATER

Small pots of soil may be freed from nematodes by a 5-minute immersion in boiling water. In shallow benches, 7 gallons of water per square foot of soil will kill them, Byars and Gilbert (8). The result of an attempt to sterilize ground beds in the Western Reserve greenhouse by directing hot water from the steam boiler was not entirely satisfactory. Considerable steam came over with the water. The soil was thoroly puddled and the excess water was slow in finding its way downward. Killing temperatures of 140 to 160° F., were obtained irregularly at shallow depths.

Examination at the end of the season of the roots of 1050 tomato plants grown in soil treated with hot water and the same number in soil steam sterilized by the buried-pipe method for one hour revealed 590 plants with galls in the former and 243 in the latter. The roots in the upper 3 inches were free from galls but the lower roots were attacked. The hot water method, therefore, was not effective in the sterilization of ground beds, even in sandy soil, where nematodes were prevalent.

GETTING THE MOST FROM A POUND OF STEAM

The Importance of Loose Soil

Great variations in depth of penetration of the steam, due to variations in the compactness of the soil, are common. Unless precautions are taken to loosen the soil thoroly, penetration is poor, especially in heavy clay and wet soil. In treating heavy clays, the most common methods are to plow and disk, or turn the soil over with a fork. In light sandy loams holes may be made at 6-inch intervals with a spading fork by prying back and forth on the handle. Since steam follows the path of least resistance, whatever the method of steam sterilizing there will be very little penetration in subsoil or any other hard, compact soil. It may be necessary to plow heavy clay twice and to disk and harrow it. For best results no lumps larger than a hen's egg should be left. In studies previously reported by the author (24) it was not uncommon to find

TABLE 20.—Effect on Steam Penetration by Thoroly Loosening the Soil Before Steaming, Pan Method

	Depth	Temperature					
		A. Loosened with fork			B. Not forked		
	In.	*°F.*	*°F.*	*°F.*	*°F.*	*°F.*	*°F.*
Experiment 1—Loose, dry, gravelly loam steamed 1 hour under high pressure	6	204	202	192	206	160	130
	8	200	190	170	160	125	100
	10	175	155	126	110	100	....
	12	150	125	100	....	....	....
Experiment 2—Heavy, wet clay steamed 1½ hours......	6	200	219	....	90	70	....
		205	200	......	80	90	....
		190	190	......	100	85	....
Experiment 3—Moist clay loam steamed 1 hour.................	6	170	....	....	120	....	....
		150	....	. ...	110	....	....
		160	....	....	130	....	....

the inner part of lumps the size of two fists 40 degrees cooler than their outer layers after steaming for an hour or two. Tables 20 and 21 summarize some of this information.

TABLE 21.—Effect of Soil Moisture on Soil Temperatures Obtained After 1 Hour of Steaming Under Pan

Experiment	Plot	Depth	Soil moisture	Average temperature
		Inches	*Pct. dry wt.*	*°F.*
1...........	a	8	26.0	200
	b	8	29.5	190
	c	8	33.0	160
2...................................	a	6	27.8	180
	b	6	41.0	125

The Importance of Dry Soil

It requires nearly four times as many heat units to raise the temperature of a pound of water 1 degree as it does a pound of soil. Consequently a soil containing 60 percent moisture requires twice as much heat to bring it to the boiling temperature as one containing 20 percent moisture. This has a practical bearing on soil sterilization, as the following experiment illustrates. A portion of a greenhouse was watered for 20 minutes with the overhead sprinkler system in July. Another portion was left as a check. After steaming by the pan method for 1 hour, it was found that at a 6-inch depth temperatures of 100 to 150° F., were obtained on the watered plots and of 160 to 195° on the dry plots. During tests in eight greenhouses, the poorest penetration was obtained in the two houses in which it was the practice to water the soil a day or so before steaming. Conversely, the deepest penetration was found in those houses where no watering had been done for six or eight weeks prior to steaming. More exact tests were made in two houses to prove this point. The data, which are given in Table 21, show that higher temperatures were obtained in the drier soils after an hour of steaming under the pan.

Similar results were obtained in wet and dry soil under the tile system at Wooster, page 43.

Fairly good penetration (150° F., to 10-inch depths) was obtained with an hour's steaming under the pan in a very hard, compact sandy loam when it was sufficiently dry (26 percent moisture). The same temperature was obtained in a moist clay soil (50 percent moisture) provided it was loose. In general, the more moisture a soil contains the more important it is to loosen it thoroly before steaming because water clogs the pores and thus hinders penetration. It is possible of course to dry out soil to the point where it becomes almost unwettable, which results in poor sterilization. Usually, even in midsummer, a soil dried 4 to 8 weeks will be found on plowing to contain sufficient moisture to permit an excellent job of sterilizing with a minimum of steam. If the soil is a little too dry for good growing conditions it will sterilize satisfactorily.

Coverings for the Soil While Steaming

When the harrow, buried-pipe, or tile method is employed it is wise to cover the soil to confine the steam and provide insulation for the upper layers. Tarpaulins, burlap sacks, old carpets, boards, and heavy building paper have been used. Canvas is effective but expensive and in large pieces heavy and difficult to move when saturated with moisture. A tough mulching paper in recent trials near Cleveland was found satisfactory. It is not too expensive, is a good insulator, can be easily and quickly rolled, and may be used many times. It is particularly suited to long, narrow beds. Papers impregnated with tar or creosote products are not recommended as these are toxic to plants.

Size of Pipe in Relation to Capacity of Boiler and Distance Away

Where larger areas are to be steamed, it is essential to provide pipes of adequate size thruout, for the quantity of steam delivered is limited to that which can pass thru the smallest pipe in the system. It is wasteful of time and money to restrict the capacity of a boiler. Recent one-acre installations have been made employing 4- and 3-inch mains, leads, and headers thruout.

TABLE 22.—Flow of Steam in Pounds per Minute Thru Standard Pipes, and Pressure-drop in Pounds per 100 ft. Equivalent Length. Velocity 4,000 ft. per Minute*

Pipe size, inches		Gauge pressure in pounds per square inch--standard pipe							
		10	15	25	35	50	75	100	125
½	Flow	0.518	0.614	0.805	0.99	1.27	1.73	2.17	2.62
	Drop	4.180	4.955	6.500	8.03	10.25	13.93	17.54	21.22
¾	Flow	.908	1.077	1.411	1.74	2.22	3.03	3.81	4.59
	Drop	2.452	2.900	3.805	4.70	6.00	8.19	10.29	12.37
1	Flow	1.473	1.746	2.287	2.82	3.61	4.91	6.18	7.45
	Drop	1.516	1.913	2.492	3.09	3.96	5.38	6.77	8.16
1¼	Flow	2.548	3.023	3.958	4.88	6.24	4.49	10.70	12.88
	Drop	1.000	1.185	1.555	1.91	2.45	3.33	4.19	5.04
1½	Flow	3.471	4.113	5.388	6.65	8.50	11.57	14.46	17.56
	Drop	.770	.910	1.194	1.47	1.88	2.56	3.22	3.89
2	Flow	5.721	6.782	8.880	10.96	14.02	19.06	24.02	28.92
	Drop	.509	.602	.788	.98	1.24	1.69	2.16	2.56
2½	Flow	8.165	9.680	12.68	15.64	20.00	27.20	34.26	41.28
	Drop	.382	.452	.592	.71	.93	1.27	1.60	1.93
3	Flow	12.60	14.93	19.57	24.13	30.85	42.00	52.88	63.70
	Drop	.272	.322	.421	.52	.66	.90	1.14	1.37
4	Flow	21.70	25.73	33.70	41.58	53.15	72.33	91.10	109.80
	Drop	.181	.214	.279	.34	.44	.60	.75	.91
5	Flow	34.12	40.45	52.96	65.32	83.60	113.70	143.20	172.40
	Drop	.130	.154	.202	.25	.32	.43	.55	.66
6	Flow	49.25	58.38	76.48	94.30	120.70	164.20	206.70	249.00
	Drop	.101	.119	.156	.19	.25	.34	.42	.51

*Reprinted with permission from the 1928 Guide of the Am. Soc. of Heating and Ventilating Engineers, by courtesy of the Crane Co., 836 So. Michigan Ave., Chicago, Ill. The table is based on Prof. Babcock's formula.

Table 22 shows a flow of 19 pounds of steam per minute thru a 2-inch pipe and 42 pounds thru a 3-inch pipe at 75 pounds pressure. The cost for 500 feet of 3-inch pipe is about $100 more than for 2-inch pipe, a difference that would be made up in one season by the saving in time in a 3- or 4-acre greenhouse. This table, which gives the flow of steam thru pipes of different sizes and under different steam pressures, should be useful in planning a soil sterilization system. It also shows the drop in pressure per 100 feet of pipe under different gauge pressures, which may aid in determining proper unit areas where part of the steaming is to be done a long distance from the boiler.

High and Low Pressure Steam

Hunt, O'Donnell, and Marshall (17), who used a pan covering 65 square feet fed by a ¾-inch lead, found that when steaming at 10 pounds gauge pressure, poorer results were obtained than at 20 pounds pressure.[5]

[5]These pressures were measured on the lead a few feet from the pan and do not refer to boiler pressure which was over 130 pounds.

One of the reasons for using a high pressure steam for nematode control is the saving of time. More heat units are driven into the soil per minute. With low pressure it is necessary to continue steaming much longer in a place and to use larger pipes and leads, to facilitate volume flow (Table 23).

TABLE 23.—Temperature, Volume, Weight, and Heat of Steam at Different Gauge Pressures

Gauge pressure	Temperature of steam	Specific volume per lb.	Weight per cu. ft.	Total heat in 1 lb. of steam (above 32° F.)
Lb.	°*F.*	*Cu. ft.*	*Lb.*	*B. T. U.*
2	219	23.57	0.042	1153
5	227	20.44	.048	1155
10	239	16.60	.060	1160
20	259	11.95	.087	1166
30	274	9.46	.105	1171
40	287	7.79	.128	1175
50	298	6.65	.150	1178
60	307	5.86	.170	1181
70	316	5.19	.192	1183
80	324	4.66	.212	1185
90	331	4.25	.235	1187
100	338	3.88	.257	1188
120	350	3.34	.295	1191

Contrary to popular belief, high pressure steam is not dryer steam. In fact, it is wetter, and that is why it is hotter, volume for volume. The heat is carried by the molecules of water vapor and the more of these there are packed into a cubic foot of steam the more heat that foot carries. All steam is saturated in greenhouse heating plants. Table 23 summarizes data for different saturated team conditions, and will help show how long soil should be steamed at 20 pounds pressure to acquire an amount of heat equal to that acquired at 80 pounds. For example, in the third column it will be seen that 11.95 cubic feet of steam must pass a given point under a gauge pressure of 20 pounds to carry 1 pound of steam containing 1,166 B. T. U.'s, or heat units, while 4.66 cubic feet at 80 pounds gauge pressure will carry 1,185 heat units. It requires 2½ times as long at the lower pressure to deliver practically the same heat to the soil.

By placing a gauge at the header and using these tables a more accurate judgment can soon be formed of how long to steam, according to the actual volume of steam going into the ground. It is much more important to know the steam pressure at the header than at the boiler. It is the heat delivered thru the header that determines the efficiency of the job, and this depends only in part upon the gauge pressure at the boiler.

It should not be inferred from the discussion that it is useless to try to steam soil with a low-pressure boiler. Fairly good results can be obtained with a boiler pressure of 15 pounds if enough time is allowed. It simply requires more volume of steam to get the same number of heat units into the soil. In one case observed, a pan employed on dry sandy loam 50 feet from the boiler gave satisfactory sterilization to a depth of 6 inches after 1 hour of steaming at 13 pounds boiler pressure. In another, tile sterilization was accomplished successfully several hundred feet from a boiler, whose pressure was not more than 20 pounds, but the time required was 12 hours.

OTHER RESULTS FROM STEAM STERILIZATION

Control of weeds.—Besides the control of nematodes, steam sterilization effects other important changes in the soil. It is claimed that the cost of steaming is offset by the complete control of weeds, especially where chickweed is abundant and several hand weedings are required in a season.

Control of various diseases.—Steaming also kills pathogenic organisms. Fusarium wilt of tomatoes on light sandy soils is almost as serious as nematodes. The fungus is particularly apt to persist along the walks near the steam mains and return lines, where the average air and soil temperatures are a few degrees higher than elsewhere. More thoro steaming is required to control this wilt than any other disease. *Aplanobacter michiganense,* which causes the Grand Rapids disease of tomato, Botrytis, the gray mold of lettuce and tomatoes, *Sclerotinia sclerotiorum,* which causes lettuce drop and timber rot of cucumbers and tomatoes, the mosaic virus, and many other pathogenes are easily killed by ordinary steaming temperatures. Altho a temperature of 140° F., is fatal in a few minutes to most fungi, it does not kill those causing damping off, tomato wilt, and tomato leaf mold. Fusarium in particular is said by Brown (9) to require soil temperatures near 180° for several hours to keep it in check. Blossom-end rot disease of tomatoes is not only not controlled by steaming but is actually made more prevalent.

The effect of steam sterilization on the water relations of soils.—The water-holding capacity of greenhouse soil is considerably altered by steam sterilization. The soil must be watered more often, using less water at a time than ordinarily, in order to maintain optimum conditions for plant growth. This is necessary because many of the soil colloids, which are partly responsible for the water-holding capacity of the soil, are destroyed by steaming. Gifford (11) has shown that top soil steamed for 45 minutes has a much reduced capillary activity. This effect is immediate and lasts for more than nine weeks. Furthermore, Smith (29) has shown that tomatoes grow differently on steamed than on unsteamed soil because of its altered water-holding capacity.

Biological effect of heating soil.—Sackett (27) and others have shown that both the nitrogen fixing bacteria, as represented by Azotobacter, and the nitrifying bacteria, Nitrosomonas and Nitrobacter, are killed by ordinary steam sterilization. A 3-hour treatment by the buried-pipe method served to destroy them in the upper 10 inches of an ordinary greenhouse soil. These bacteria were found in the soil again after three months. The ammonifying bacteria, on the other hand, being largely spore formers, are not destroyed by steaming. Perhaps this is why a number of workers have found an increase in ammonia after heating. It may also explain the injurious effect sometimes following the sterilization of soils rich in organic matter. As soon as the soil has cooled, these ammonifying bacteria which have survived convert the organic nitrogen into ammonia. In the absence of nitrifying bacteria to convert this into nitrites and nitrates it may accumulate to the point of becoming toxic to plants.

Excess soluble salts.—Much work has been done to determine the effect of heating soils for varying lengths of time and at different temperatures on the amount of soluble organic and inorganic materials in them, Gustafson (16). Besides breaking down the soil colloids and upsetting the balance of biologic life, moist heat is believed to dissolve many of the salts present in the soil. On drying, these salts are deposited on the surface of the soil particles in great abundance and are brought into solution more readily. Nitrites and ammonia, particularly, are increased. Ammonium carbonate appears to be the most injurious salt in many heated greenhouse soils. Nitrates may be increased in some cases and decreased in others. Soils rich in organic matter show a higher total soluble salt content after heating than do soils poor in organic matter. The lime requirement may be either increased or decreased by heating.

The soluble salt content may be increased by steaming, even to the point of becoming detrimental to plant growth. Increases of 2 to 10 times the original salt content have been obtained. When the total soluble salt content is already as high as is consistent with good growth, doubling the amount may result in noticeable injury.

The most common effects on tomatoes are poor set of fruit, much of which is rough, on the lower two clusters, and excessive vegetative vigor of the whole plant. In extreme cases, as when sterilizing is done for the first time in a rich soil, more severe effects develop. The authors have seen tomato plants actually dwindle in size and thousands of lettuce seedlings rot at the crown when grown in soil just after its first steaming.

Fortunately, this condition can be quickly remedied by thoroly leaching the soil with an abundance of water. Experiments in Ohio have shown that the equivalent of 8 to 12 inches of continuous rainfall is sufficient to remove the excess of soluble materials. By applying this amount of water to one soil a salt content of 2½ to 3 percent was reduced to two-thirds of 1 percent.[6] Adequate drainage must be provided during the leaching or the salts will simply be driven down into the soil a few inches, soon to return to the surface as the soil water moves upward.

However, the danger from excess soluble salts should not deter one from sterilizing when the time comes to cut down the losses from nematodes, wilt, and streak. Usually a grower has adequate warning of the need to sterilize so that he may reduce applications of manure for a year or so previous to steaming. He may then substitute mineral side dressings while reducing the organic content of the soil. If he is also prepared to leach at the first signs of excess salts, the soil should not suffer any ill effects from steam sterilization. Lettuce is considered by many to be a safer crop than tomatoes to follow the first soil sterilization.

INCREASE IN YIELDS FROM STEAM STERILIZATION

Mention has been made of one carefully conducted experiment on a sandy soil in which the increased yield of tomatoes alone, due to steaming, netted more than $1,500 an acre. In a half-acre greenhouse on heavy clay at Cleveland yields of tomatoes before sterilization were 2,000 to 2,500 baskets. After tile were installed at a cost of $800 the yield was 5,000 baskets. In houses where nematodes and Fusarium wilt have gained a foothold it is not at all uncommon for yields to increase 20 to 50 percent as a result of steam sterilization. If losses from soil-harbored pathogenes have reached an annual toll of 10 to 20 percent of the crop a tile installation of even the most expensive type will pay for itself in one to three years.

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[6]Data kindly supplied by I C Hoffman of the Ohio Agricultural Experiment Station.

USEFUL HINTS

1. Every grower should provide himself with one or two dairy thermometers. These are strong, may be read quickly, cost less than a dollar, and their use will enable him to determine how deep the steam has penetrated the soil. Readings should be duplicated to avoid false conclusions.

2. The steam pressures maintained in the greenhouse close to the header or the pan as well as at the boiler should be noted. A steam gauge is a valuable part of the regular pipe assembly. It should at least be used on the assembly farthest from, and the one closest to, the boiler for the difference in time required to get good results will be the greatest at these points.

3. Raising the initial steam pressure from 10 to 100 pounds increases the flow of steam about four times. Also at stationary pressures of 10, 50, or 100 pounds, increasing the size of pipe from 1 inch to 2 inches, increases the flow approximately four times (Table 22).

4. Turning on too much steam when operating close to the boiler with high steam pressure may cause blow-outs in tile lines. Four-inch tile are suggested for such places.

5. It is well to have a by-pass near each riser or set of pans thru which the water can be eliminated from the line before turning steam into the tile, or buried pipe or pans, as the case may be. This is especially important when sterilizing at a long distance from the boiler.

6. Immediately after turning off the steam, either in buried-pipe or tile lines, provision for free entrance of air should be provided. Otherwise there is danger of clogging the underground lines with mud drawn in by the suction created when the steam condenses.

7. Since nematodes and the tomato Fusarium wilt fungus are most difficult to eradicate under the walks and near the return lines, it is necessary to steam these regions thoroly. It is best done by placing a special line of tile close to the walk and steaming this line by itself.

8. Tees, elbows, short-length tile, and header tile with holes to fit over ⅜-inch nipples are now available on the market.

9. It is now the practice with many growers to lay the tile on a thin layer of crushed limestone and to cover the joints with the

same material to facilitate the escape of steam into the soil and to postpone any tendency for the joints to clog. This is particularly advantageous in heavy clay soil.

10. Tile lines need not be level. If they slope it should be away from the header rather than toward it.

11. From 1 to 2 square feet can be sterilized per horse power per hour with buried tile, 2 square feet with pans, and 3 square feet with buried pipe. The tile will heat the soil much deeper than the pan and with very much less labor than the buried pipe.

12. A tough mulching paper makes a good, cheap covering for soil to be steamed by either the buried-pipe or tile methods.

13. Care to prevent the re-contamination of sterilized soils is important. A general clean-up should accompany soil sterilization. A 2 to 3 percent formaldehyde or lysol solution may be used to sterilize concrete, tools, walks, floors, and the packing house. Shoes and gloves may be washed, dipped in hot water or formaldehyde, or steamed before starting the next crop.

SUMMARY

PART I

The root-knot nematode *Heterodera radicicola* is the worst pest found in Ohio vegetable greenhouses and causes annual losses of more than $100,000.

Nematodes have been found to overwinter out-of-doors in several places in Ohio.

The chief environmental factors affecting Heterodera are temperature and humidity. The thermal death-point was found to be 118° F. at a 20-minute exposure in loam soil. Very little activity occurs in soils maintained at 50 to 56° F. All stages are easily killed by desiccation. Soil spread in a 2-inch layer in flats in a warm part of the greenhouse became air-dry and free from living nemas in eight days.

In a commercial greenhouse on a sandy loam nemas were present at a depth of 27 inches.

Several methods of control are discussed. Experiments with more than 30 chemicals and chemical combinations gave very little indication that a satisfactory and economical control can be obtained with nemacides. One application of Cyanogas plus napthalene flakes at 1,750 pounds each per acre gave partial control, but at such strengths the method was uneconomical in comparison with steam sterilization.

PART II

Hot water treatments of soil in ground beds did not prove successful in destroying nematodes.

Of the four principal steam sterilization methods employed, the harrow system was found very unreliable and failed to give killing temperatures below 4 inches. The inverted-pan method was fairly satisfactory where only one high-temperature crop was to follow and gave killing temperatures at depths of 5 to 10 inches. Several improved types are described. The cost of steaming with the pan varied between 0.6 and 1.2 cents per square foot.

Where two high-temperature crops were grown each year it was necessary to sterilize to greater depths, for which the buried-pipe and buried-tile methods were much more satisfactory. Killing temperatures, 140 to 150° F., were easily obtained at depths of 9 to 18 inches with pipe buried 10 to 16 inches, and at 12 to 24 inches with tile buried 12 to 18 inches. The time required varied between 2 and 10 hours, depending upon the quantity of steam available per unit area steamed and upon the moisture in the soil.

The buried-tile method has three advantages. It requires the least labor to operate, it produces killing temperatures to greater depths than any other method, and it may be used in sub-irrigating a crop or in leaching excess salts from the soil.

Both 3- and 4-inch irrigation tile have been successfully used for more than 12 years. Tile lines need not be closer than 18 inches from center to center and probably should not be farther apart than 2 feet, depending upon the depth to the bottom of the tile, which may vary between 12 and 16 inches.

Steam was not directed successfully from an underground header much farther than 100 feet in one direction or 75 feet in each of two directions.

The size of a unit area steamed at a time varied greatly in successful commercial installations, being as low as 100 square feet per 100 horse power in some and 2,600 square feet in others. A very satisfactory size was from 800 to 1,200 square feet.

It was of great advantage to have soil dry and loose at the time of steaming. Six or eight weeks was not too long a time to let ground beds stand without watering in late fall prior to steaming.

In the pipe or tile methods a covering of canvas, boards, or heavy mulching paper aided in retaining the heat.

Pipe lines of sufficient size to carry the desired quantity of steam are essential in any method of steam sterilization. It is suggested that a pressure gauge be used on the assembly at or near the header since the pressure diminishes with distance from the boiler. By knowing this header pressure the quantity of heat entering the soil can be calculated from the tables given and the proper time allowed for thoro sterilization. A dairy thermometer is useful in measuring the soil temperature at different depths.

Advantages of using high pressure steam are that smaller volumes and, therefore, less time are necessary to deliver a given quantity of heat to the soil.

Certain important physical, biological, and chemical effects of steam sterilization on the soil are briefly reviewed. Among these are lowering the water-holding capacity of the soil by the destruction of soil colloids; death of nitrifying and nitrogen-fixing bacteria but not the ammonifying forms; and increase in the proportion of soluble organic and inorganic matter and, hence, of total soluble salts. These may reach injurious concentrations.

Excess soluble salts were leached from the soil by providing adequate drainage.

In general, steam sterilization pays as soon as crop losses from nematodes, Fusarium wilt and other soil-harbored pathogenes amount to 10 percent of the crop. The cost does not exceed 2 cents per square foot even with the most expensive tile installations.

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